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NAVY SYSTEM EFFECTIVENESS MANUAL NAVMAT P3941-B PROPOSED

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13. ABSTRACT

This manual is offered as a general guide to concepts and tools for Navy and contractor program managers, project managers and project engineers. It provides an overview of the Navy's current concepts of system effectiveness and its elements; provides management-level guidance in implementing system effectiveness; shows how system effectiveness aids the decision - making process; and summarizes tools and techniques currently available for use in system acquisition programs.

The approach taken is to select and present a consistent body of approaches, definitions, formulations and categorizations for use in Navy system effectiveness programs.

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NAVY SYSTEM EFFECTIVENESS MANUAL

NAVMAT P3941-B Proposed

by

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FOREWORD

The growth of modern Naval power abroad along with other threats to our national security has brought about a spiraling increase in complexity of Naval systems to meet increasing levels of threat. This has resulted in problems of achievable operational effectiveness in an era when effectiveness is more crucial than ever before. At the same time, economic pressures at home require that a maximum pay-off in effectiveness per dollar be achieved and that the investment of other resources be realistic. To achieve this, our full potential for designing effectiveness into systems must be realized.

The Navy's investment into the development of analytic and management design-decision techniques for ensuring required levels of effectiveness has been substantial over the past decade. Considerable progress has been made under the Systems Performance Effectiveness (SPE) program in developing useful approaches, techniques and tools for system effectiveness planning, design and evaluation. This manual summarizes the Navy's current effectiveness concepts and the tools presently available, and discusses their application to the Navy's acquisition process. Navy program managers, project managers and project engineers are urged to use this manual as a guide to designing for increased effectiveness through application of the "effectiveness approach" and the tools available for its implementation in system engineering programs.

The first edition of this manual was published in 1967 (NAVMAT P3941), followed by an updated version in July 1968 (NAVMAT P3941-A). Since then, the continued development of tools and procedures together with further experience in their application has created the need for substantial revision. As a consequence, the manual has been rewritten to incorporate new material to meet current needs within the Naval Material Command. Comments or recommendations concerning the contents of this manual should be forwarded to Code 4100, Naval Electronics Laboratory Center, San Diego, California 92152.

ADMINISTRATIVE INFORMATION

This manual was prepared for the Naval Electronics Laboratory Center by D. T. Hanifan of The Harbinger Corporation, Santa Monica, California under Contract N0024-73-R-0087, under the technical direction of H. Greenstein, Product Assurance Division (Code 4100) in partial fulfillment of the Division's responsibilities under the Systems Performance Effectiveness Program. Work was performed under Project SF099-90-002, Task Area 1622 (NELC R124), during the period July 1971 - September 1973.

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CHAPTER ONE: INTRODUCTION

1.1 Purpose of the Manual

This manual is not intended to be a training manual or technical reference work for system effectiveness techniques. Rather, it is offered as a general guide to concepts and tools for Navy and contractor program managers, project managers and project engineers. Its specific purposes are to

- provide an overview of the Navy's current concepts of system effectiveness and its elements,
- provide management-level guidance in implementing system effectiveness,
- show how system effectiveness aids the decision-making process, and
- summarize tools and techniques currently available for use in system acquisition programs.

Although the literature on system effectiveness contains varying formulations and definitions of terms, no systematic attempt is made here to review and compare the various approaches and definitions used by different authors and organizations. The approach taken is to select and present, to the extent possible, a consistent body of approaches, definitions, formulations and categorizations for use in Navy system effectiveness programs.

It is hoped that greater familiarity with the concepts and tools of system effectiveness analysis will lead to more-widespread implementation in Navy programs--and to realization of the increased effectiveness per dollar for Navy systems that can be achieved.

This manual is supported by detailed procedure- and methodology-manuals at both NAVMAT and using command levels for application of the various subdisciplines of effectiveness (reliability, maintainability, etc.).

1.2 Application

The approach outlined in this manual is applicable to all Navy systems throughout the acquisition life cycle from Concept Formulation through Operational Phases, although major emphasis is placed here on Concept Formulation, Validation and Full Scale Development. The criticality of conducting system effectiveness analysis depends on the level of study and design effort and becomes more significant for more-complex system and total force studies. The approach should be specified whenever operational effectiveness or system value is considered to be an important basis for selection of system design and/or support system alternatives, or when system optimization comprises a significant effort.

System effectiveness analysis should be applied by NAVMAT and using commands for generating requirements and selecting major system options. Prime and associate contractors and major subcontractors should apply the techniques for optimization of major systems/subsystems.

The techniques discussed in this manual are flexible and may be tailored to a range of budget and schedule requirements, although the useful level of analysis will depend on the sensitivity of life cycle cost and system value to variation in major effectiveness variables, on the criticality of the system in the Navy's overall weapon system program, and on the degree of risk inherent in the acquisition program for the system in question. The system effectiveness/system value (SE/SV) methodology described herein is specifically aimed at reducing system development program risks through rational decision-making processes which match total system characteristics to operational requirements and conditions well in advance of deployment.

1.3 Benefits to Management

The modern concepts of system effectiveness analysis grew out of the need for a rational basis for making design decisions in complex system acquisition programs. Since, from economic and scheduling necessities, design hypotheses must be tested before major investments are made, an analytic structure is required within which all elements of the system can be related to each other and to the whole in terms of their contribution to potential effectiveness. Furthermore,

since resources are limited and lower-level design goals are often conflicting, compromises or trade-offs are required, and this requires a common measure or criterion. In addition, a framework is required which facilitates communication among the technical and management members of the design team. Obviously, if a model of the system can be manipulated to measure the system rather than the system itself, considerable savings in time and resources can be achieved.

Effectiveness analysis provides a framework and method for selecting and optimizing systems within the broader context of missions and objectives, and has evolved into a central tool for engineering and management decision-making. Within the inherent limitations of any analytical approach, used appropriately during the system engineering process the system effectiveness approach provides one of the critical ingredients for:

producing a system within acceptable, defined limitations of

- time
- resources of dollars, management, manpower and facilities
- technology and state-of-the-art

which performs its assigned mission(s) with acceptable effectiveness and cost

- under stated environmental conditions
- within an established mission-time frame

when deployed and operated under conditions of

- defined types and levels of support
- established policies and doctrine
- interaction with other systems with which it must interface

The benefits to management of implementing a systematic program of system effectiveness analysis increase with the complexity of the mission, system and acquisition program. These benefits include the following:

- Management can exercise better control since prediction of the system's effectiveness is in a form which enables potential trouble-spots to be pinpointed early, and provides visibility to aspects of the design process which are not otherwise visible until much later.

- Accountability is improved since an objective, quantitative measure of effectiveness for major elements provides an important measure of performance of the group responsible.

- System effectiveness formulation provides a rational and readily-communicated vehicle for stating requirements, and thus reduces the communication gap between user and producer within the Navy, Navy and contractor, contractor and subcontractor, and among personnel within all organizations.

- The iterations required to produce an effective final design may be reduced since the interactions of major design factors and system elements are explicit and more-readily comprehended.

- A basis is provided for determining the sensitivity of overall effectiveness to the contributions of the various design factors, thus providing an objective means for allocating resources among competing design and "ility" groups or functions.

- When associated with cost, schedule, and mission analysis (which establishes worth and utilization factors as well as the effectiveness criteria), effectiveness analysis and evaluation of competing concepts, designs or plans provide the most complete and credible basis available today for deciding among alternatives and optimizing total system design in terms of overall objectives and resources.

Ultimately, of course, all decisions depend on the judgment of responsible decision makers and depend heavily on many factors which are only marginally or not at all susceptible to quantitative analysis. Furthermore, even the best quantitative analyses in the "real world" are subject to uncertainties and risks (which are also estimated in an adequate analysis). Hence, effectiveness analysis does not produce decisions but is simply one of the bases for decision. Nevertheless, it is an extremely valuable tool for decision since it involves a systematic examination of the possibilities, and provides a rational way of estimating the consequences of the interaction of systems of variables which would be difficult or impossible to accomplish on an intuitive basis.

In summary "... the virtue of analysis is that it is able to make a more systematic and efficient use of judgment than any of its alternatives. The essence of the method is to construct and operate within a "model"--an idealization of the situation appropriate to the problem. Such a model ... introduces a precise structure and terminology that serve primarily as a means of communication, enabling the participants in the study to make their judgments in a concrete context. Moreover, through feedback... the model helps the decision-maker, the analysts, and the experts on whom they depend to revise their earlier judgments and thus to arrive at a clearer understanding of the problem and its context."*

*Quade, Edward S., "Introduction and Overview" in Goldman, Thomas A. (Ed.), Cost Effectiveness Analysis, Praeger, N.Y., 1967, pg. 3-4.

CHAPTER TWO: THE CONCEPT OF SYSTEM EFFECTIVENESS

2.1 System Effectiveness: An Element of System Value

Selection and optimization of a system require that competing concepts and designs be considered in relation to each other and to their uses in order to acquire the system which has the greatest operational value. Thus, an important decision criterion is an index of value associated with competing configurations that accounts for and balances the system credit and debit factors as well as the relative frequencies and worths of the various uses of the system. On the credit side is the effectiveness of the system with respect to each of its uses (missions). On the debit side is the cost or penalty associated with achieving that effectiveness, including acquisition and operational dollar costs, acquisition time and resource costs, and penalty costs to other systems through such things as competitive use of support systems. Where multiple missions exist for a system, the relative frequency and military worth of each mission must also be considered. If the military worth of missions, effectiveness of systems, or penalties are expected to change over the system's life cycle, then "degradation" or "improvement"* factors also need to be accounted for -- particularly if rate of degradation or improvement varies among the various missions or competing system concepts. A classification of these factors is shown diagrammatically in Figure 2-1. An early formulation for relating some of the factors quantitatively is the value index given by Equation 2-1 of Figure 2-2 -- the so-called Index of Navy Defense Effectiveness, E_d.

Actually, Equation 2-1 is illustrative and would be applicable as given only in special cases. In application, the formulation E_d would be made in light of the particulars of the systems and missions being considered. In illustration, a somewhat more-general formulation is

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* The concept of system degradation as a function of time is familiar to everyone. The possibility of "improvement" also exists, and examples are common of such system "learning" processes as "availability growth" resulting from elimination of early failures of defective parts, correction of errors in maintenance and operating data, shaking down of the logistic support system, technician learning through on-the-job experience, design improvements, and the like.

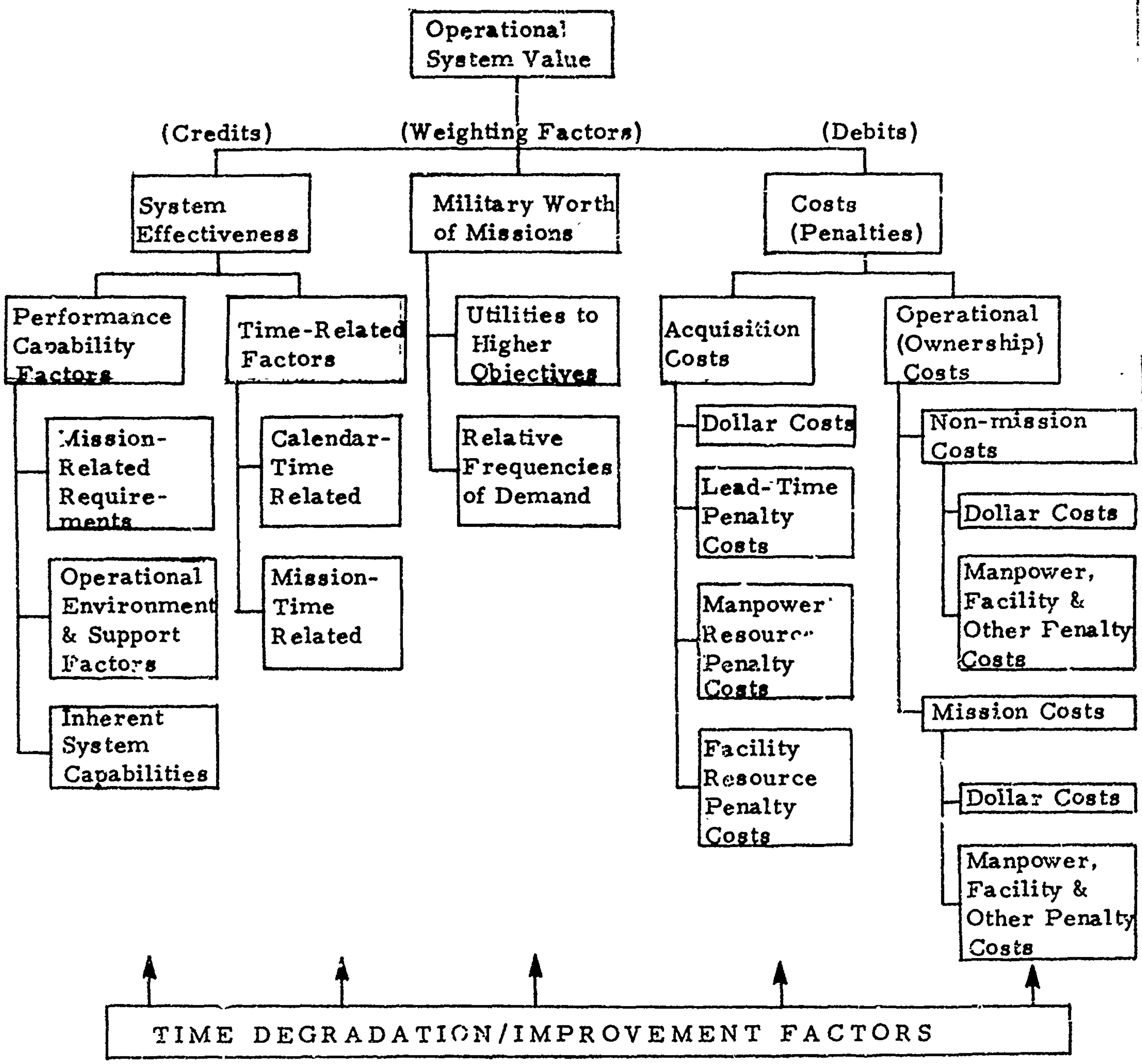

Figure 2-1. Factors to be considered in formulating an index of system operational value

EQUATION	DEFINITION OF TERMS
Equation 2-1 $E_d = \frac{W E_s}{E_t(C_a + C_o)}$	E_d = Index of Navy Defense Effectiveness W = Military worth of the system's mission E_s = System Effectiveness E_t = Index of time effectiveness (actually an index of degradation of W as a function of time) C_a = Acquisition costs (dollars and equivalent dollar costs of other penalties) C_o = Operational costs (dollars and equivalent dollar costs of other penalties)
Equation 2-2 $E_d = \frac{\sum_j \sum_i N_{ij} W_{ij} E_{ij}}{C_a + \sum_j C'_{o_j} + \sum_j \sum_i N_{ij} C''_{o_{ij}}}$	E_d, C_a as in Eq. 2-1 N_{ij} = Number of repetitions of the ith mission type in the jth year W_{ij} = Military worth of the ith mission-type in the jth year E_{ij} = Effectiveness of the system with respect to the ith mission-type in the jth year C'_{o_j} = Operational costs in the jth year which are not dependent on number of mission runs $C''_{o_{ij}}$ = Average operational costs per mission-run for the ith mission-type in the jth year

Figure 2-2. Illustrative mathematical formulations of the Index of Navy Defense Effectiveness as an index of system value

provided by Equation 2-2 of Figure 2-2. However, in many cases cost and effectiveness terms are interdependent and a simplistic use of such equations is not possible. Actually, to obtain a valid decision index, before applying a formulation of this type each system being evaluated should have been optimized such that the terms represent optimal values in a "cost-effectiveness" sense. For instance, effectiveness would have been defined as functions of acquisition dollar, time and resource costs as well as operational dollar and other penalty costs. These functions would then have been used to determine the most-favorable (optimal) values of effectiveness and costs. These values would then be used along with the other required information to determine the overall index of value for each system.

From the foregoing discussion, it can be seen that a quantitative measure of system effectiveness is essential if the relative "values" of competing system concepts and designs are to be estimated. In the next section, the system effectiveness term is examined in more detail.

2.2 Effectiveness: Net Usable Performance Related to Required Level

System Effectiveness (E_S) can be defined as "a measure of the extent to which a system can be expected to complete its assigned mission within an established time frame under stated environmental conditions."* Although various figures of merit have been used to represent this measure, the most generally useful and directly interpretable measures are quantitative and stated in probabilistic terms. Thus, system effectiveness may be defined more specifically as "the probability that a system can successfully meet an operational demand throughout a given time period when operated under specified conditions."*

In addition to probability of success, the performance-requirement ratio is also useful since this may give some insight into the degree by which the requirement is not met or is exceeded -- which may be an important consideration, particularly if appreciable risk and uncertainty exist in the estimate of the system's performance or if the validity of the requirement is in question. However, such ratios need to be interpreted with caution as will be shown.

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*Systems Effectiveness, compiled by Systems Effectiveness Branch, Office of Naval Material, January 1965 (AD 659-520).

Before proceeding further, it will be helpful to discuss the meaning of performance, capability and related terms as used in this manual. The term "performance," when used to describe the output of a system, is meant in its broadest sense and includes the total set of usable outputs. Thus, the performance of a system at any given time may vary anywhere from the maximum potential performance of which it is capable under the most favorable conditions, through various reduced levels resulting from extrinsic or intrinsic factors, to zero performance (as in system failure). Unfortunately, it has also become common practice to use the term "performance" as a short-hand term in lieu of "maximum (potential) performance," sometimes called "performance capability," which assumes dependable operation in a specified environment as will be discussed later. In some instances, this manual also uses the term performance in this way, but the meaning should be clear from context. In any case, however, the term performance refers to the actual level or amount of output(s) of a system without regard to the level or amount required. Further, unless clear from context, the term "performance" is used in the sense of net or usable output where reliability, support system, environment and other factors are taken into account.

In no case are the terms "performance" and "Capability" to be used synonymously. As discussed later, the term Capability is defined within a system effectiveness modeling context as the "probability that the system's designed (or maximum) performance will allow it to meet mission demands successfully assuming that the system is available and dependable." Thus, Capability implies a comparison of (1) designed performance (the required minimum performance) with (2) the level of performance needed to carry out a mission under consideration -- whether or not these demands are within the original system specifications.

Preserving the distinction between Capability and performance, and distinguishing between the general use of the term performance to denote actual or usable output at a given time and its special use to denote maximum or designed performance, will reduce much potential confusion.

2.2.1 Effectiveness vs. Usable Performance

In some cases the requirement (effectiveness criterion) may be difficult to establish because an analysis of higher-level objectives involving missions and systems outside the scope of a particular design effort has not been accomplished. In such cases, the success criterion either has a certain arbitrariness or simply is not available, and a system performance measure is all that can be reported. In that case, either the system with the greatest performance would be selected or, perhaps, the one which provides the maximum performance per cost. However, such measures should not be reported as "effectiveness" values since they are not related to a valid required level of performance derived from objectives. The existence of such situations does not invalidate the effectiveness concept, but rather points to the need for appropriate higher-level studies by the user for establishing meaningful requirements.

Examples of system performance measures which have frequently been reported without reference to a required level include percent target destruction, circular error probability, channel capacity, probability of error, ton-miles/day, passenger-miles/day, etc. In all such cases, higher-level analyses need to be performed to establish the criteria for acceptable level of system performance before statements can be made about the system's effectiveness as opposed to performance.

To illustrate the difference between measures of performance and effectiveness, suppose a transportation system is being evaluated, and that its net output is measured in ton-miles/day. What is its effectiveness -- i.e., how effective is it?

While it makes sense to say that a system which is capable of transporting, say, an average of 100 ton-miles/day is more effective than one which transports only 50, we don't know how effective it is unless a goal has been specified -- nor do we know, for instance, whether it has been over- or under-designed. It makes no sense to say that the system's effectiveness is 100 ton-miles/day. Strictly speaking, the 100 ton-miles/day is its average performance.

To determine the system's effectiveness, we would need to know how many ton-miles/day are required and, since the system's performance may vary depending on numerous factors, we need to know more about it than its average, such as the distribution of ton-miles/day. Thus, we might determine that the requirement for a given

mission is 150 ton-miles/day and that, while the average performance is 100 ton-miles/day, its probability distribution of ton-miles/day is given by curve A in Figure 2-3.* According to the curve, the system will transport 150 ton-miles/day or greater with a probability of 0.25. Thus, its probability of "success," which tells us how effective the system is likely to be in meeting its requirement, is 0.25 with respect to the given mission. Performance is specified by the "probability distribution" of ton-miles/day, the effectiveness criterion or objective is "deliver at least 150 ton-miles/day," and its effectiveness is 0.25, which is the probability of meeting the criterion (meeting the mission demands). Another measure which might be of interest is its average performance-requirement ratio, which is 100/150 = 0.67. This has been interpreted as showing the extent to which a system meets its requirement, but as will be seen this is not necessarily a good measure of "extent" since it can be misleading.

An effectiveness of 0.25 is quite low and we would probably conclude that the system is unacceptable. If another system with greater effectiveness were not available, either an effectiveness improvement program or design of a new system would be indicated, depending on cost and lead-time factors. On the other hand, if the type of mission permitted, two "systems" might be used since the average performance-requirement ratio would then be 200/150 = 1.33, which would appear to provide an acceptable margin over the requirement. In fact, however, under assumptions of independence, the distribution of performance for two such "systems" operating together (when combined under the appropriate rules of mathematical statistics) is as shown in curve B of Figure 2-3. According to curve B, two systems will transport 150 ton-miles/day or more with a probability of 0.68, the new level of effectiveness. Curve C is the three-system case, which has an effectiveness of 0.88, which is still not a particularly high probability of success -- even though the average performance-requirement ratio is 300/150 = 2.0.

From the foregoing, it is seen that using average performance in the performance-requirement ratio led to easily misinterpreted results. It was used in the illustration because of its use by some

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*Strictly speaking, a probability distribution as ordinarily defined expresses the probability that the quantity being measured takes on the value x or less. Figure 2-3 actually plots one minus that probability, i.e., the probability that the quantity is x or greater.

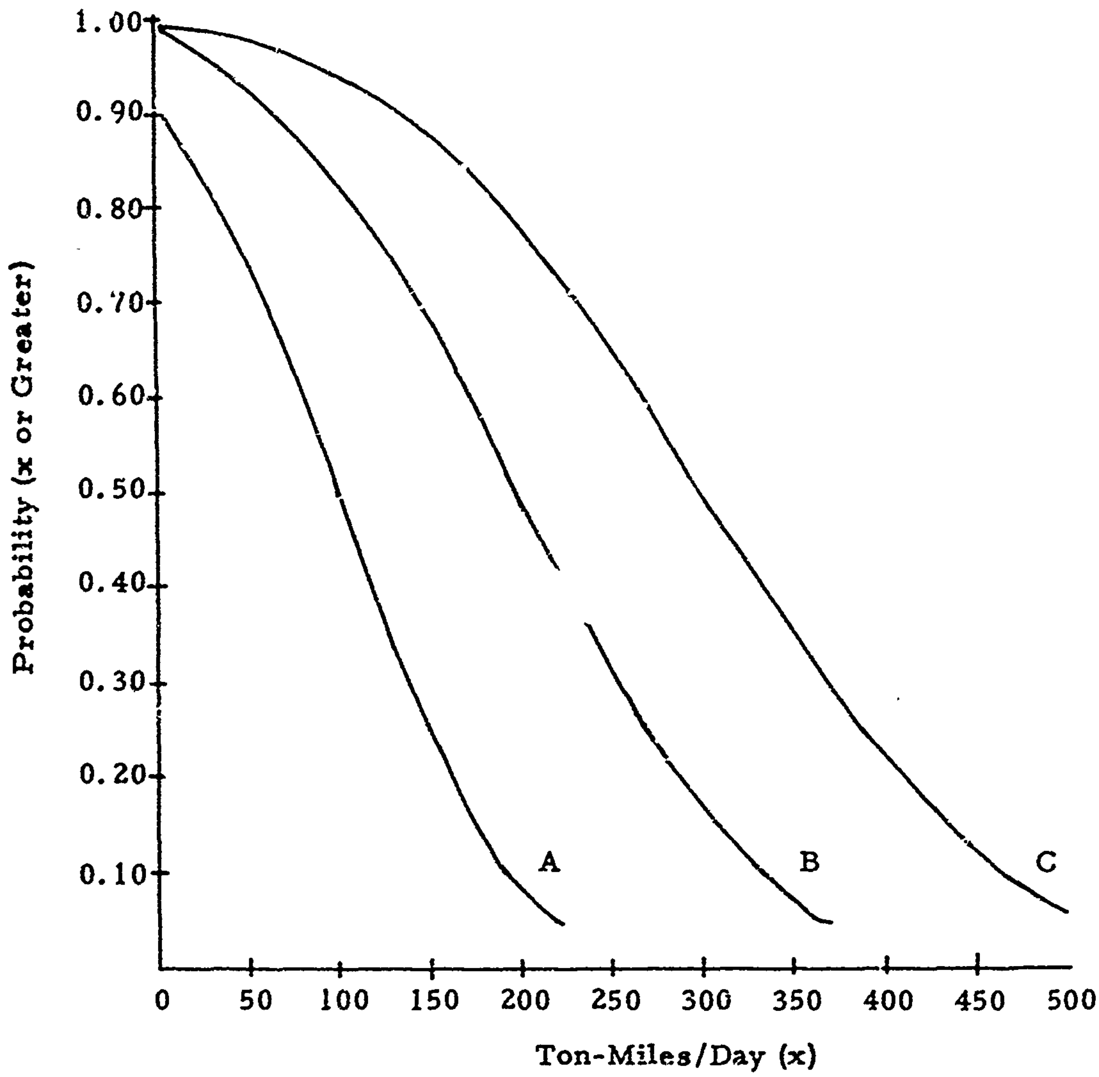


Figure 2-3. Hypothetical performance "distributions" (see text)

analysts. A better approach would be to specify a ratio at some level of probability such as, say, 90 percent, i.e., we desire an effectiveness of 0.90. Since we want a performance level the system will achieve at least 90 percent of the time, we pick off the 0.90 points on the curves in Figure 2-3, which are as follows for each "system:" A = 5, B = 66, C = 136. Thus, the "90 percent" performance-requirement ratios are: A = 5/150 = 0.033; B = 66/150 = 0.440; C = 136/150 = 0.907. This makes more sense as a measure of "extent" if in addition to the 150 ton-mile/day requirement we also require that effectiveness be at least 0.90. For instance, the ratio for case B indicates that we have met 44 percent of the required 150 ton-miles/day at a probability of 0.90. If the requirement had been only 66 ton-miles/day, we would have an effectiveness of 0.90 and a performance-requirement ratio of 1.0.

As a general procedure for systems in which fractional performance may have some meaning, effectiveness numbers will be more-readily interpreted if supplemented by a performance-requirement ratio at a probability which is equal to the minimum required probability of success (effectiveness).

In fact, the effectiveness and the performance-requirement ratio are simply two ways of looking at the same data. Effectiveness is a probability associated with a "fixed" performance whereas the performance-requirement ratio (as defined) associates performance with a "fixed" probability. Both require the distribution of performance.

2.2.2 The Effectiveness Model

By now it should be clear that system effectiveness is a measure of the system's net usable performance in relation to the type and amount of performance required by its mission. Not only is the system's designed or theoretical performance capability taken into account, but also the many operational conditions and system attributes which tend to degrade that performance -- including environmental and operational influences, inherent tendencies to fail or degrade with time, etc. -- together with the resources for restoring the system or preventing such degradation. The predicted or measured effectiveness, then, is the probability of successfully performing a mission given the net effect of all the positive and negative influences on performance in an operational environment.

The proper accounting of these factors requires the formulation of an analytical framework or mathematical model. This is called the "effectiveness model" and its formulation requires specification of the details of system characteristics, mission profiles and functional requirements, planned support systems and policies, projected demand rates, and use doctrine.

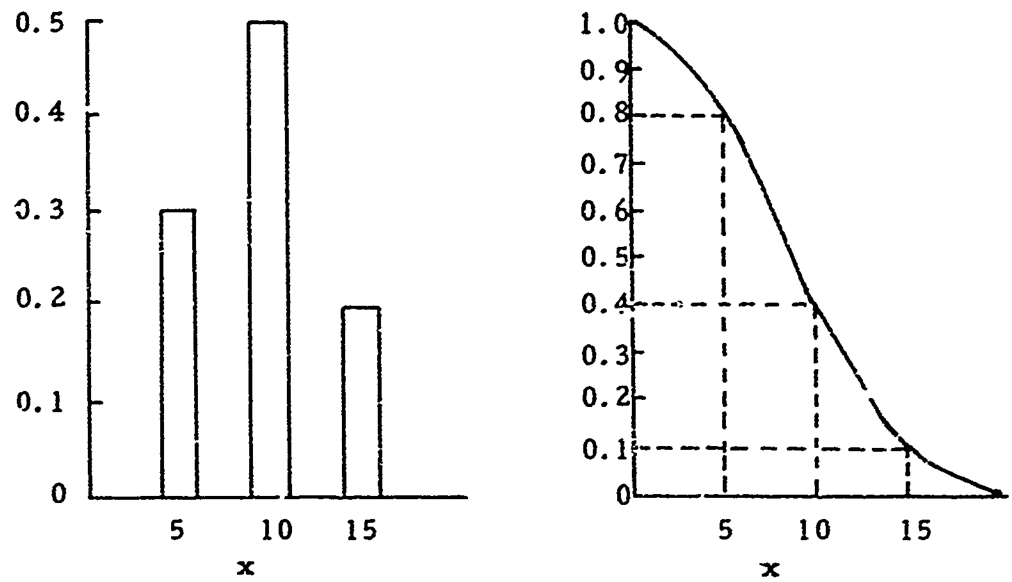
The structure of such models must always be specific to the particular system/mission under consideration. However, the conceptual framework within which the models are structured tends to be fairly consistent across broad classes of systems.

The general notion of an effectiveness model assumes that threat analysis and analysis of mission profiles provide a time-oriented specification of system functions to be performed together with critical performance levels and durations along each of the performance dimensions. It is further assumed that analysis of the system's characteristics in relation to the mission situation provides a specification of its performance, including possibilities of failure or degradation, with respect to the performance dimensions associated with its functions. Thus, both demands made by the mission on the system's performance <u>and</u> the system's (net or usable) performance capability in response to demands are defined in such a way that they can be compared.

Generally speaking, both mission demands and system performance will be variable due to the statistical nature of (1) threats or other factors which define mission requirements, and (2) system processes which define the presence or absence of various levels of performance. As a result, effectiveness of the system in meeting a particular type of demand depends on the probability that the demand on performance is at a given level, and on the probability that the performance of the system is at least equal to or greater than the given level of demand.

This is illustrated graphically in Figure 2-4, where curve (a) is the probability density of demands, i.e., the probability that demand on performance is $\underline{x}$, and curve (b) is the probability that usable system performance is $\underline{x}$ or greater. For instance, an underwater target might be at a range of 5 miles (the demand) 30 percent of the time, and a given sonar system might, after discounting environmental factors, "inherent" failure and degradation possibilities, operator problems and the like, detect and classify a target at 5 miles or less 80 percent

(a) (b)



Demand on Performance (Target range, miles)

Performance (Max range in miles)

(c)

(1) Demand Level	(2) Prob. of Demand	(3) Prob. of Perf.≥Demand	(4) Joint Prob. of Demand & Perf. (2) x (3)
5 mi.	0.3	0.8	0.24
10 mi.	0.5	0.4	0.20
15 mi.	0.2	0.1	0.02
			Σ = 0.46
Effectiveness (overall prob. of success) = 0.46			

Figure 2-4. Example system effectiveness computation where mission demands and system performance are variable but independent

of the time. According to curve (a), target distances (demands) are conveniently defined at three levels as shown in column (1) of the table (c) in Figure 2-4 with the associated probabilities given in column (2). System performance, as given in curve (b), can meet these demands or better with the probabilities given in column (3). The product of probabilities in each row gives the joint probability, in column (4), that the demand is x and that the performance is x or greater. The sum of the joint probabilities in column (4), in this case, is 0.46, which is the effectiveness or probability of success assuming independence of demands and performance.

In curve (a) of Figure 2-4, demand levels are represented as discrete for simplicity of illustration. In practice, demand densities and performance level distributions would frequently be continuous. The equivalent of the above operation in continuous form is stated mathematically in Equation 2-3 given in Figure 2-5, which expresses system effectiveness as the a priori probability that a system will be able to meet any level of mission demand chosen at random from the total distribution (density) of demand possibilities. Unavailability of performance due to failure, damage or other factors is included since performance can be zero. The equation can be expanded to include any number of functions and performance dimensions. Different effectiveness formulations can essentially be regarded as special cases of this equation in its continuous or discrete form.

Equation 2-4 in Figure 2-5 extends the concept to missions in which partially meeting a demand has some value or utility. This is particularly important where degradation as opposed to total failure may occur. For instance, target damage may have some value even though the objective is total "kill," communication system degradation may affect speech intelligibility rather than totally blocking transmission, etc.

A frequently encountered special case occurs when the distribution of demands has not been derived and the requirement on level of performance is specified as a fixed number; in that case no credit is given for degraded states which have some probability of meeting lower-level demands. Effectiveness is underestimated in such cases.

The foregoing is a very general way of looking at the effectiveness concept. It provides a modeling starting point which can encompass a wide variety of systems, missions and criteria. However,

EQUATION	DEFINITION OF TERMS
Equation 2-3 $E_s = \int_0^\infty F(x)\, g(x)\, dx$	E_s = a priori probability that the system will be able to meet any level of mission demand chosen at random from the total distribution of demands $F(x)$ = probability that a system's performance is at least $\underline{x}$ (one minus the distribution function) $g(x)$ = probability that the demand level is $\underline{x}$ (density)
Equation 2-4 $E_s = \int_{x=0}^{\infty} \int_{y=0}^{\infty} u(y\|x)\, f(y)\, g(x)\, dy\, dx$ (If dependencies exist between performance capability and demand, $f(y)$ is replaced by $f(y\|x.)$)	E_s = as in Eq. 2-3, except E_s is expected extent of success and fractional success may be attributed to performance less than demand levels $f(y)$ = probability that performance level is $\underline{y}$ (density) $u(y\|x)$ = utility of performance level of $\underline{y}$ when demand level is $\underline{x}$ $[0 \le u(y\|x) \le 1$ & $u(y\|x) = 1$ for $y > x]$ $g(x)$ = as in Eq. 2-3

Figure 2-5. General equations for System Effectiveness which assume variable (distributed) performance and demand levels

typical formulations have started at a somewhat less-general level through the use of particular classes of conditional probabilities (effectiveness "elements") which structure the modeling process. These probabilities are related to a generalized way of looking at a large class of Navy missions; they can also be readily related to typical system acquisition program elements and functions -- hence their practical utility. The next section presents this commonly-used contemporary approach to effectiveness modeling with the understanding that other approaches can be used and, for some classes of problem, may be preferable or even necessary.

2.2.2.1 Major Elements of a System Effectiveness Model

In Figure 2-1 system effectiveness is represented as a function of performance capability factors and time-related factors. Aside from special cases, a system may be thought of as being required at some point in calendar time (which can be regarded as random for many Navy defense systems), after which it must dependably perform a mission for a specified period of time (mission-time) given its designed performance capabilities. The effectiveness of a system, then, depends on its availability, dependability, and capability in relation to the mission. The following definition of system effectiveness is given by MIL-STD-721B (which is similar to one provided by the Weapons System Effectiveness Industry Advisory Committee [WSEIAC]*):

> SYSTEM EFFECTIVENESS: A measure of the degree to which an item can be expected to achieve a set of specific mission requirements, and which may be expressed as a function of availability, dependability and capability.**

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*Weapons System Effectiveness Industry Advisory Committee (WSEIAC), Final Reports AFSC-TR-65-1, 2, 3, 4, 5, 6, January 1965.

**MIL-STD-721B "Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors, and Safety" 25 August 1966.

This definition may be expressed as

$$E_s = f(A, D, C) \qquad (= \bar{A}' [D] \bar{C} \text{ in the WSEIAC approach})$$

where, according to MIL-STD-721B:

A = AVAILABILITY: A measure of the degree to which an item is in the operable and committable state at the start of the mission, when the mission is called for at an unknown (random) point in time

D = DEPENDABILITY: A measure of the item operating condition at one or more points during the mission, including the effects of Reliability, Maintainability and Survivability, given the item condition(s) at the start of the mission. It may be stated as the probability that an item will (a) enter or occupy any one of its required operational modes during a specified mission, (b) perform the functions associated with those operational modes.

C = CAPABILITY: A measure of the ability of an item to achieve mission objectives given the conditions during the mission.

These are usually expressed as probabilities. For instance, in the WSEIAC approach:

$\bar{A}$ is the Availability vector (a vector array of various state probabilities of the system at the beginning of the mission), and $\bar{A}'$ is its transpose

$[D]$ is the Dependability matrix (a matrix of conditional probabilities over a time interval, conditional on the effective state of the system during the previous time interval)

$\bar{C}$ is the Capability vector.

The three major elements of system effectiveness together with some of the more-important factors which influence them are shown diagrammatically in Figure 2-6.

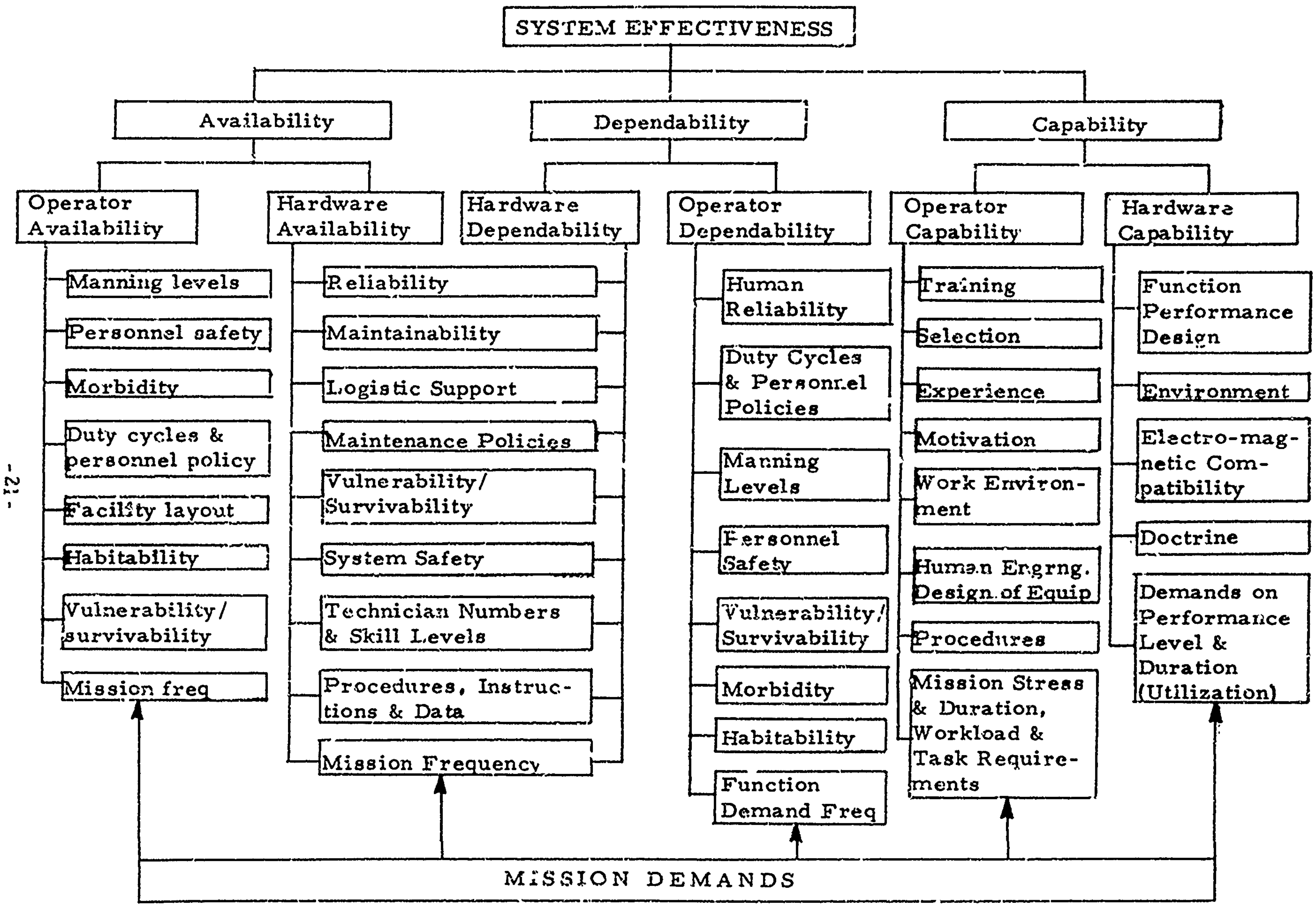

Figure 2-6. Some factors affecting system effectiveness

Although it may not be entirely clear from the definitions, the three terms are mutually exclusive: great care must be exercised in modeling to guarantee that the same data are not included in more than one term. Further explanation may help to clarify the terms.

2.2.2.1.1 Availability

Availability, as ordinarily defined, is simply the probability that the system is in an "up" and ready state at the beginning of the mission when the mission occurs at a random point in time, i.e., is ready to operate within allowable response time with all mission-required functions capable of operating within design specifications. Availability (of hardware) is a function of the reliability and maintainability characteristics of the system (neglecting, for the moment, safety, logistics, human factors, and vulnerability/survivability properties of systems). For sufficiently long operating periods, availability of a system (with zero warning time) can be expressed in terms of its MTBF (mean time between failures) and its MTTR (mean time to restore or mean active repair time) given that it has failed:

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

where the subscript $\underline{i}$ indicates that this is "Inherent" Availability, i.e., ideal availability assuming only active components of corrective maintenance time, i.e., no waiting for spares and technicians; no "detection" or "administrative" time; no down time due to preventive maintenance or servicing; immediate availability of technical manuals, test equipment, and software; etc.

If, in addition to corrective maintenance, preventive maintenance is also included, the computed availability is commonly called "Achieved Availability:"

$$A_a = \frac{MTBM}{MTBM + MADT}$$

where MTBM is mean time between maintenance (both corrective and preventive) and MADT is mean active downtime, which includes the active (non-waiting) time elements of both preventive and corrective maintenance.

Both A_i and A_a are frequently found in specifications imposed on the producer or contractor where the producer or contractor is not held responsible for extra-system logistic and other user factors beyond his control. While "Achieved Availability" comes closer than "Inherent Availability" to representing the state of affairs in an operational situation, there are still significant discrepancies between so-called "Achieved" and Operational Availabilities. The measure of ultimate concern to the <u>user</u>, and thus of greatest relevance in system effectiveness analyses, is Operational Availability.

In an operational situation, all of the sources of non-operable time, active and inactive, including "software" downtime, supply and administrative delay times, corrective and preventive maintenance times, are combined into the term "downtime;" "Operational" Hardware Availability (A_{oh}), then, is a function of MTBM and mean downtime (MDT):

$$A_{oh} = \frac{MTBM}{MTBM + MDT} .$$

A_{oh} is a probability which assumes availability of an operator if one is required. In man-machine systems, Availability (A_{op}) of the necessary operating personnel (in "up" condition) must also be determined. Operational System Availability, A_o, then, is:

$$A_o = A_{op} A_{oh} .$$

This measure of availability accounts for the effects of logistics, maintenance policies, manning, priorities, etc., and is therefore the measure of choice in a system effectiveness analysis and of greatest interest to the user. Use of A_i to compute E_s, on the other hand, would provide something like an "inherent system effectiveness," which could lose much of the point of doing such an analysis. A considerable loss

of analytic and design-decision power would be lost since logistic problems (to mention only one factor) provide one of the major sources of loss of effectiveness in Navy systems in the fleet. In one case of a major sonar system, for instance, Inherent vs. average measured Operational Availability of seven ships was 0.960 as compared to 0.320. Similar examples abound in most if not all types of systems.

As mentioned above, Inherent and Achieved Availability are frequently used in hardware specifications where the contractor is not held responsible for logistics and the operational environment (as he frequently cannot, particularly if he is a lower-tier contractor). Nevertheless, system effectiveness studies performed by the Navy (particularly the user) for the purpose of generating requirements, or by major system contractors, should use Operational Availability. Except for very early gross estimates, this generally requires a more-complex model structure, but the payoff in operational effectiveness fully warrants the additional effort.

A factor which is sometimes overlooked in Availability formulations is Operator Availability in a man-machine system. Thus, the formulation of A_{op} may be a critical determiner of Operational Availability, A_o, since the probability of the operator being in an "up" state (within allowable response time) may not be particularly high. This is a function of manning policies, work duty cycles, training, safety, health factors, administrative procedures, personnel vulnerability in combat situations, location of duty areas and living quarters in relation to systems, personnel cross-utilization among systems or functions, and numerous other factors which determine the availability of adequately-trained operators at the system site within allowable response times.

In addition to Operator Availability, Maintenance Technician Availability has an impact on the mean-downtime (MDT) term of Hardware Availability since delays due to "waiting for technician" are included. Again, manning policies and priorities plus demand rate (determined by the MTBM terms of all the equipments/systems he services) determine technician waiting time.

Estimating these Availabilities, except in the simplest cases, generally requires that a mathematical model be constructed and exercised which accounts for the interrelation of the many factors across the total system. Total ship (base, etc.) models implemented by computer, utilizing simulation or equivalent techniques, are frequently the

only feasible means of doing this. Such models not only estimate Availability for given support conditions, but also provide a means for determining optimal manning, logistics, maintenance scheduling and related policies.

2.2.2.1.2 Dependability

Dependability is the probability that, given the system was available, it will continue to operate throughout the mission either (1) without a system-level failure, or (2) if it fails, it will be restored to operation within some critical time-interval which, if exceeded, would result in mission failure. "Without a system-level failure" means that the output of the system in response to demands during the mission is within design specifications, considering the effects of the environment. For instance, failure of a redundant item when only one of two is needed to produce the system output would not imply system failure; failure of both, however, would produce system failure. Various Dependability cases exist depending on the criteria for system failure, and each requires a different model. Examples of such criteria are: (1) no failure allowable (reliability of serial systems); (2) no system-level failures allowable, but certain element failures may occur n-j times without repair (reliability of systems where j out of n parallel elements must function): (3) no system-level failures allowable, but certain element failures may occur with repair a given number of times (reliability with repair of parallel system elements where number of spares and number of technicians are specified); (4) system-level failures allowable if downtime is less than a specified time; (5) other cases also exist. (The first three of these cases, together with Availability, are within the capability of the Generalized Effectiveness Methodology (GEM), a Navy-developed computerized model which is discussed in Appendix B).

As in the case of Availability, Dependability is also a function of the reliability* and maintainability characteristics of a system (not to mention vulnerability/survivability, safety and others). However, as mentioned above, many models exist depending on the type of system/mission and the criteria for failure. The simplest one (no failures in a simple, serial system) eliminates the maintainability term and is

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*Reliability should include not only "inherent" failures, but failures induced by maintenance actions as well.

simply the equation for system reliability given in Figure 2-7, Equation 2-5. If a system-downtime-per-failure of time $\underline{t}$ or less means that the mission is not failed but can continue after repair of the system. then under certain assumptions an equation such as Equation 2-6 of Figure 2-7 is an appropriate expression for Dependability. If the probability of having more than one failure is negligible, an approximation which has been used frequently is given by Equation 2-7.

The equations in Figure 2-7 are given as illustrations only, since operational situations are not generally as simple as this. For instance, assumptions such as exponentially distributed downtime usually do not hold except as convenient, but usually inaccurate, approximations. (The exponential distribution is more likely to be a reasonable approximation for inherent repair times than for downtime.) Furthermore, human performance terms are not included (except as implied in MDT) and sources of operator "failure" and system downtime due to operator "outage" must be considered.

As in the case of Availability, Dependability of a man-machine system must obviously include the effect of Operator Dependability in addition to Hardware and Software Dependability. Careful examination of a mission profile and the functional requirements may reveal many potential sources of functional failure and downtime due to operator actions or absence of actions. These may be in either of two forms: human induced hardware failure due to operator "goofs;" or failure to perform operator functions due to conflicting duties, lack of alertness, removal from duty by sickness, accident or damage, error, etc. Many of these are similar to those which affect Availability, except that they occur during the mission rather than prior to or at its beginning. In some cases it will be more convenient to include them in a combined hardware-personnel model; in some cases, separate consideration is valid. Where two sources of "undependability" are not interdependent, they can be estimated separately and combined to estimate Total Man-Machine Dependability. Thus where independence can be assumed, if D_h is Hardware Dependability and D_p is Operator Dependability, then Overall System Dependability is

$$D = D_h D_p.$$

EQUATION	DEFINITION OF TERMS
Equation 2-5: No failures allowable, serial system $D \equiv R = e^{-\lambda T}$	D = Dependability R = Reliability of a serial system, constant failure rate λ = Failure rate = 1/MTBF T = Operating time or continuous mission time
Equation 2-6: Allowable downtime per failure $D = \exp[(-\lambda T)e^{-t/MDT}] = R^{e^{-t/MDT}}$ where MDT & t << T and downtime is exponentially distributed	D, λ, T as in Eq. 2-5 MDT = Mean downtime t = Maximum allowable downtime per failure, i.e., exceeding t means failure of mission
Equation 2-7: Allowable downtime per failure (approx.) $D = R + (1-R)\,M_o$ where probability of more than one failure is negligible, and MDT & t << T	D, R, MDT, t as in Eqs. 2-5 and 2-6 M_o = Operational hardware maintainability, the probability that downtime is no greater than t

Figure 2-7. Illustrative equations for simple cases of Hardware Dependability

Frequently, however, Dependability of the hardware may be affected by Operator Dependability (as well as by Maintainer Dependability, which must appear in the hardware term). In that case, joint distributions of operator and hardware factors must be developed in order to compute Overall System Dependability.

Care must be exercised, however, that the same personal effectiveness factors are not included in both the Dependability and Capability terms. To prevent this, it is sometimes better (where possible) to incorporate all the operator effectiveness factors into a single conditional probability (personnel subsystem effectiveness) and multiply this times the "hardware" effectiveness number. However, this is often not possible because substantial dependencies may exist. An example of the dilemma which can arise is given by the problem of human error (estimated by "human reliability" practitioners). This could either be treated as a failure analogous to hardware failure and included in the Dependability term, or as a performance capability factor and included in the Capability term. Although conceptually it probably is treated more easily in the Capability term, it usually makes little difference where it appears providing it, or terms implying it, appear only once.

2.2.2.1.3 Capability

Capability is probably the most-misunderstood of the three effectiveness terms. It is the probability that the system's designed performance will allow it to meet mission demands successfully assuming that the system is Available and Dependable. This term takes into account the adequacy of the system performance elements to carry out the mission when operating in accordance with the system design specifications as affected by the environment. Both machine and human modules of the operable system are included. Mission analysis, including mission profiles with quantitative demand levels, are required to formulate a Capability model.

The definition of Capability, then, implies that when the system is carrying out a mission where demands are within its design performance limits, and under environmental conditions that are within its specified limitations, it might be assumed that its Capability (stated in probabilistic terms of mission success) is exactly what its designers computed or determined by test. This is rarely 1.0, as is sometimes

assumed in effectiveness computations, except in vastly over-designed systems or very special cases. Usually, however, Capability is even less than theoretical computations or test results would indicate since demands or environment may not be precisely within specified limits, electromagnetic compatibility problems exist, etc., plus the fact that the human performance part of the Capability term may have been overestimated or even assumed to be 1.0 (which is the assumption when the human performance term is effectively left out). Thus, the effectiveness modeler must usually modify the system performance numbers obtained from hardware designers in order to obtain a more-accurate estimate of Total System (man-machine system) Capability. This is frequently difficult and requires explicit consideration of the human performance term in cooperation with human factors specialists. An approach to "personnel subsystem effectiveness" modeling should be used which provides outputs in a form compatible with the other effectiveness submodels. The form of such models, at the most general level, is similar to the form of the general effectiveness equations given in Figure 2-5. The major difficulty is in obtaining suitable data; carefully-controlled estimation processes must frequently substitute for empirically-obtained data due to the budgets and schedules of typical programs.

Assuming that sources of operator "outage" are included in the Dependability term, the (human) Capability term, C_p, is the probability that the operator responds successfully to mission demands assuming (1) that he is Dependable, (2) that the hardware is Dependable, and (3) that the hardware is Capable. The term will include human "error" and will reflect the effects on operator performance of training, experience, change of performance as a function of mission stress and duration, motivation factors, etc. Some of these can be estimated from experimental data or operational records, but many are at present known only qualitatively and their effects must be estimated on the basis of judgment. The temptation is to leave them out. However, their inclusion through the cooperative efforts of the modeler (who structures the form of input), human factors specialists, and operational personnel, will invariably lead to a more-valid effectiveness analysis output -- and may provide the means for identifying sources of effectiveness-degradation which can be corrected at the outset rather than later at great expense.

If Hardware Capability, C_h, is the probability that the hardware will successfully meet mission demands assuming it is Available and Dependable and assuming the operator is Available, Dependable and

Capable, and C_p is as defined above, then under assumptions of stochastic independence, Overall System Capability, C, is

$$C = C_h C_p.$$

2.2.2.1.4 Utilization

The foregoing formulations assume that a defined, specific mission profile is being analyzed, so that the modeling and computation of system effectiveness incorporates all utilization factors (fractional use-time or demand-time of system functions). If this is not the case, and computations of Dependability and Capability are referenced to total mission-time, then a given "function time" may be obtained by multiplying mission-time by the function's Fractional Utilization Time, i.e., average of the ratio of function use time to mission time. Therefore, if the model is defined such that Utilization, U, is not implied in the "D" and "C" terms, then system effectiveness is defined in terms of "system function effectiveness, E_i," i.e., $E_s = f(E_1, E_2, \ldots, E_i, \ldots, E_n)$, where there are n functions used during the mission, and system function effectiveness of the ith function is

$$E_i = g(A_i, D_i, C_i, U_i).$$

2.2.3 Multiple Missions

Even if a system is to be used for more than one type of mission, it is still advisable to define system effectiveness with respect to each mission, since this information is of considerable value to planners. However, comparison of competing system concepts will usually also require that an index of value of each concept be estimated in terms of the total mix of mission uses.

Although the formulation of "system effectiveness" proposed by some practitioners is identical to the index of value as defined in Section 2.1, the distinction is worth preserving, i.e., the distinction between indices of value, which include considerations of military worth of the missions performed (as well as costs and penalties), and effectiveness, which is a probabilistic measure related to the system's

success in carrying out the mission whatever its worth. Where the index of value does not include costs or penalties, but does contain weighting factors for utilization across missions and military worth of the missions themselves, the special term "Index of System Effectiveness" is proposed for standard Navy use to preserve the distinction between a "success probability" and a weighted index of success probabilities used as a decision criterion. "Index of Value" should be used where costs and penalties are also incorporated.

One way to formulate an Index of System Effectiveness (I. S. E.) where multiple mission-uses exist for a single system is as follows: Suppose a system is or can be used N_{ij} times to perform the ith mission in the jth year; that military wirth is W_{ij} for the ith mission in the jth year; and that the system effectiveness is $E_{s_{ij}}$ with respect to the ith mission in the jth year. Then

$$\text{I. S. E.} = \Sigma\Sigma\, N_{ij} W_{ij} E_{s_{ij}} \qquad \text{Equation 2-8}$$

This turns out to be identical to the numerator of the equation for "Index of Navy Defense Effectiveness," the index of value given in Figure 2-2 (Eq. 2-2). N_{ij} could also be replaced by U_{ij}, fractional utilization, although that would not as clearly take into account the possibility that "faster" systems might be able to perform more missions, which could be important for some types of missions and systems (e.g., transportation systems, search systems under certain demand conditions, etc.).

2.3 Special Tools and Techniques

A large variety of mathematical models, computer programs, methods and procedures have been formulated for System Effectiveness/ System Value (SE/SV) applications and new ones appear every year. Any comprehensive review of them would be outside the scope of this manual. However, the next two sections and the Appendices summarize some of the more important tools and techniques with which the manager should be familiar. In particular, a general understanding of approaches to modeling and estimating distributions is important (Appendix A). Also, familiarity with some of the Navy models/methods (or sources)

which are available for modeling and predicting, evaluating, trade-off and design disclosure, will be useful (Appendix B). A summary of useful computer programmed models is given in the Handbook of Systems Effectiveness Models.* Risk and Uncertainty, considered in Section 2.3.2, is a particularly important conceptual tool for the manager.

2.3.1 Modeling Techniques

Numerous approaches to mathematical modeling of mission/system processes exist and may be required depending on particulars of the modeling problem. Reviewing them in any meaningful depth would require a substantial reference work in its own right and is clearly outside the scope of this manual. However, a few general observations concerning the nature of such models together with a simple illustration (in Appendix A) will help to give the manager some insight into their formulation.

Since the processes represented by SE/SV models are rarely if ever deterministic in nature (i.e., do not have exactly predictable outcomes), the basic modeling requirement is to represent the probabilistic or stochastic nature of the processes. This is achieved by representing them as "finite random processes" which account for the alternative possibilities and variability that exist.

In general, the existence of some system state will lead to one or more possible events (actions, tasks, etc.) whose probabilities of occurrence depend on internal and/or external system factors. Each possible event or sequence of events leads to a new system state which, in turn, implies one or more alternative events, and so on. This is generally represented graphically as a network or branching tree diagram. The branches at each juncture have associated conditional branch probabilities and each event(s) transitioning to subsequent states has associated probability distributions of variables related to effectiveness, cost, etc. A graphic model of the process (network or tree diagram) is used as the basis for, and guides formulation of, the

*Naval Electronics Laboratory Center, Handbook of Systems Effectiveness Models, Technical Document 187, 30 June 1972. (For availability to qualified users, contact NELC, Code 4100, San Diego, California.)

mathematical model. A simple illustration is given in Appendix A. Appendix B summarizes three proceduralized methods or models which the manager may find useful: the Generalized Maintainability Method (GMM), the Generalized Effectiveness Method (GEM), and Design Disclosure for Systems and Equipment (DDSE).

2.3.2 Risk and Uncertainty

In any rational approach to decision-making, evaluation of risk and uncertainty is necessary and may have considerable impact on planning-decisions. "Risk" is used to refer to the probability of undesirable outcomes based on analysis of objective data. Thus, the risk of running out of spares during a mission can be computed from reliability data, and can be reduced to any desired level by improving reliability, increasing the number of spares, providing on-board repair capability, or some combination of these approaches. Similarly, the risk of repair-time exceeding some given value can be determined from the repair-time distribution.

"Uncertainty" is generally used to refer to subjective estimates of the probability of undesirable outcomes. For instance, the probability of cost or schedule overrun must frequently be based on subjective estimates of cost and time distributions. In either case, however, the analytic procedures can be similar, and for decision-making purposes, both risk and uncertainty may need to be combined in a single analysis. In such cases, an "estimated risk" is derived.

Generally speaking, in any process subject to variability, at least two types of risk or uncertainty can be identified. First, there is risk or uncertainty which has its source in "real-world" variability. Thus, the time to repair a system failure may vary from one repair to another due to differences in skill level of maintenance technicians, varying motivations and mission stresses for a given technician, type of failure, differences in surrounding circumstances and time-pressures, etc., so that the exact repair-time is never predictable. However, the distribution of time can be defined by observing many repairs such that the probability can be stated that repair-time will not exceed any given value. This accounts for "real-world" variability since it recognizes the fact of the underlying variability of the process.

The second source of variability arises from our limited ability to estimate the "real-world" distribution of a variable or parameter. For instance, if we had estimated a repair-time distribution by taking five observations of repair-time and fitting a distribution curve to the points, we would have an "estimate" of the distribution, but ten points would have given a better estimate and 50 points an even better one. Thus, there is an inherent risk in the estimate of any point on the distribution or any of its parameters such as the mean or standard deviation, due to the fact that the distribution is based on a "sample" rather than all of the repair-times (which could never be achieved). This is expressed by the "sampling distribution" associated with a parameter or percentile of a distribution, or by a "confidence interval" derived from the sampling distribution. A confidence interval on the mean, for instance, is an interval within which a sample mean could be expected to fall with some stated probability. It can also be thought of as an interval which has a stated probability of containing the true or population mean. Obviously, the wider the interval the less certain we are of the true value of the mean. Thus, we would expect the width of the confidence interval to decrease as the number of observations increases. In fact, given the number of observations and the data or form of distribution, a sampling distribution and associated confidence interval can be calculated or approximated for any property of a distribution, including the percentiles as well as the mean.

The relation between the distribution of a variate such as repair-time, accuracy, etc., and the sampling distribution of some property of the distribution is illustrated by Figure 2-8, where a repair-time distribution (from Appendix A) is shown with a hypothetical sampling distribution of the mean. The horizontal bar defines the symmetric 90 percent confidence interval (from the 5th to the 95th percentiles of the sampling distribution). While curve A tells us that there is a 90 percent probability that repair-time is 1.05 hours or less and the estimated mean repair time is 0.50 hours, curve B, the sampling distribution of the mean, tells us that due to the sample size used to estimate the distribution (curve A), there is a 90 percent chance that a sample mean will lie somewhere between 0.43 and 0.57 hours. This is equivalent to saying that if a large number of samples of the same size were taken, 90 percent of the sample means would be expected to fall within the interval. We could also make such statements as "the probability is 0.95 that the mean is 0.57 hours or less."

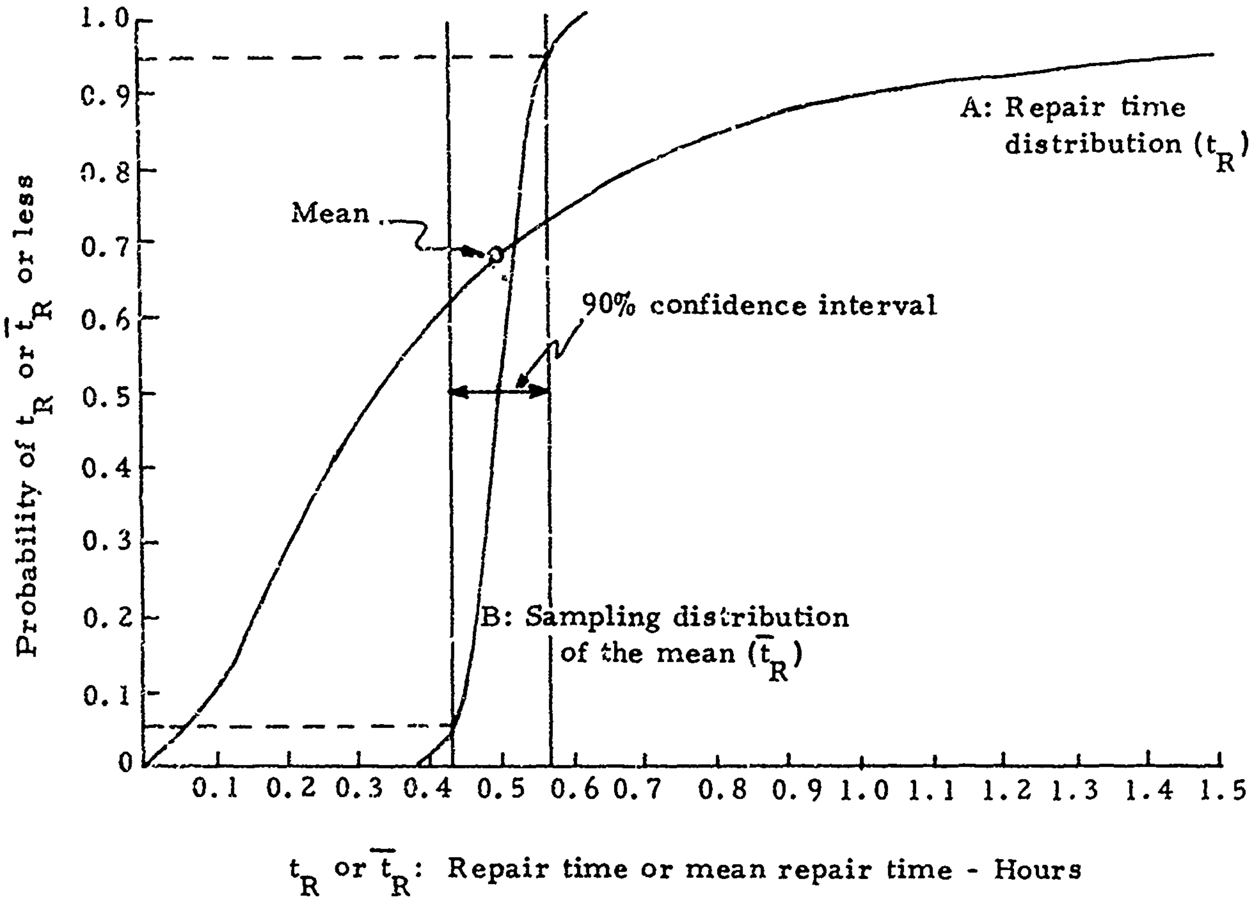

Figure 2-8. Repair time distribution with sampling distribution of the mean

For distributions which were estimated subjectively rather than on the basis of objective sampling by observation, something roughly akin to a sampling distribution may be arrived at which, in subsequent analytic procedures, can be used in a similar way. However, the basis and approach for this are beyond the scope of this manual.

One type of risk estimation which should accompany SE/SV analyses is to estimate the probability that effectiveness, schedule, cost or system value will be worse than the predicted value by varying amounts. This can be achieved by computing or estimating sampling distributions or confidence intervals on all parameters of the model and combining them, using appropriate statistical methods, to provide a distribution of the overall output measure. For instance, in the sample SE computation (Appendix A), "confidence intervals" on each of the distribution parameters (actually, "sampling" distributions) could have been combined appropriately to produce either of the estimated distributions of SE shown in Figure 2-9.

If we had obtained curve A, we would have less confidence in the computation of SE than if we had obtained curve B. For instance, curve A indicates a probability of 0.25 that the true value of SE might actually be less than 0.63, while curve B indicates a probability of only 0.08. In both cases, the "best" estimate is 0.70 (the "mean"). Curve A might represent the low quality of input data early in the acquisition program, while curve B might represent higher quality data obtainable in later phases. Decision confidence is low for curve A (we are 90 percent sure that SE falls somewhere between 0.54 and 0.86), whereas decision confidence is higher for curve B (we are 90 percent sure that SE falls somewhere between 0.62 and 0.78). If we wanted to use an estimate of SE for which the estimated risk is 10 percent that the true value could be lower, their respective 10th percentiles would force us to assume that SE = 0.57 for curve A and SE = 0.64 for curve B, even though in both cases the "best estimate" was 0.70.

A similar use of distributions can be made to assess risk in the case of cost, schedule, downtime or any other measure of interest. Where objective ("hard") data are not available, subjective estimates of upper, lower and central values of the range of variability may be used to provide points on "subjective" distributions, after which curve-fitting procedures can be used to find the "best-fit" distribution. The subjective distribution is then used to evaluate "estimated" risk. In such cases, it is generally advisable to estimate distributions at lower

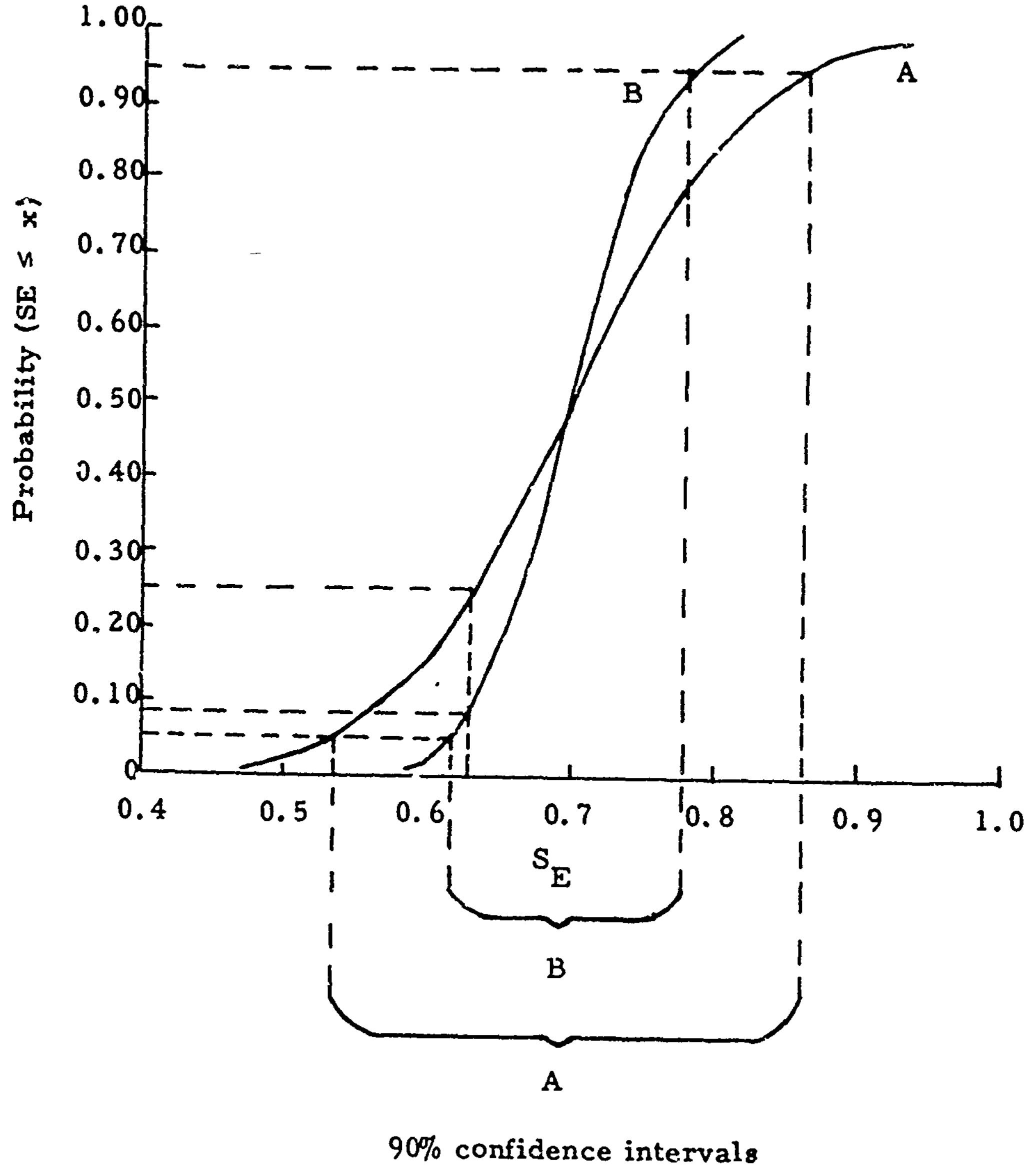

Figure 2-9. Hypothetical distribution of system effectiveness used to evaluate risk

levels of indenture and combine them to provide the overall distribution. For instance, if overall cost is the sum of 20 item costs, the cost estimators would provide high, low and central ("average") estimates to represent cost uncertainty for each item. The analyst would then fit distributions to each set of estimates and combine them by convolution to estimate the overall cost distribution. Management, then, would have the option of using the "best" or "mean" cost, or of using a cost associated with some estimated risk.

2.4 The Effectiveness Disciplines

In addition to the traditional design engineering functions which determine hardware performance capabilities, a large number of engineering specialities or disciplines have become established in response to the growth of system engineering and system effectiveness analysis in modern engineering management. These are known as the "effectiveness disciplines" since they are related in various ways to assuring the effectiveness of the operational system through control of one or more factors which influence the Availability, Dependability or Capability of a system. Unfortunately, the concept of an integrated system engineering and effectiveness program arose relatively late in the evolution of engineering management, and as a result, considerable overlap and cross-purposes may be found in typical specialty engineering groups. This must be guarded against by a carefully-conceived effectiveness management plan implemented within the system engineering program.

The effectiveness disciplines include:

- Reliability
- Maintainability
- Logistic Support
- Human Factors (including Training, Human Reliability, Human Engineering, Habitability, Manning, etc.)
- Safety
- Vulnerability/Survivability
- Electromagnetic Compatibility

These are the disciplines which are generally most central to the effectiveness program. Numerous others have varying degrees of relationship, depending on the type of system and program, and must also be integrated into the acquisition program. They include such

specialties as silencing, system mass properties, operating doctrine, value engineering, transportability, producibility, security engineering, electronic warfare, standardization, etc.

How the effectiveness elements and disciplines are related to system effectiveness is illustrated in the system state model given in Figure 2-10. The various effectiveness engineering functions or disciplines which have an impact on each term (state or event) are noted. Together, they constitute the scope of the system effectiveness activity which determines the effectiveness of the system and provides inputs to the effectiveness model. In a well-conceived engineering program, the effectiveness modeling function provides a basis for integrating these disciplines through its central, coordinating function as the analytic arm of the system engineering function. The relationship of effectiveness and its major variables and factors is also suggested in Figure 2-6 given previously.

Following are brief descriptions of the more-central effectiveness disciplines (sometimes referred to as the "ilities") which can have a major impact on the effectiveness of systems through participation in system engineering and design.

2.4.1 Reliability (R)

MIL-STD-721B defines Reliability as "The probability that an item will perform its intended function for a specified interval under stated conditions."

The reliability function in engineering programs is one of the oldest and best-established of the effectiveness disciplines. Typical program activities include modeling, prediction, failure mode and effects analysis, allocation, test and evaluation, specification of reliability design approaches, parts selection, design review, reliability research, and other activities necessary to provide assurance that the system's failure characteristics are compatible with the required Availability and Dependability of the system. The relation of the MTBF (a major reliability parameter) to Availability and Dependability has already been discussed in earlier sections.

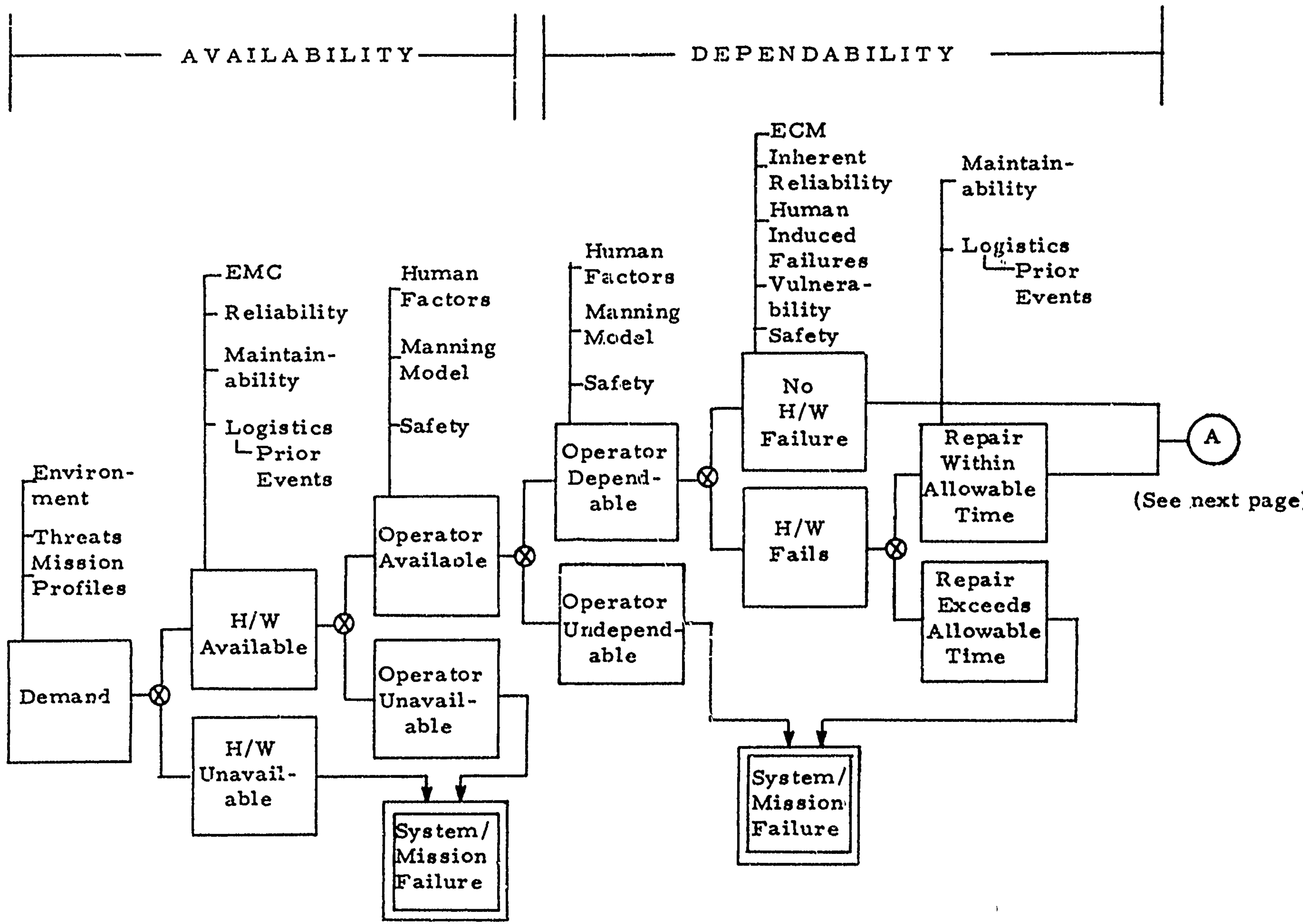

Figure 2-10. Example top-level system effectiveness diagram with related tools or disciplines

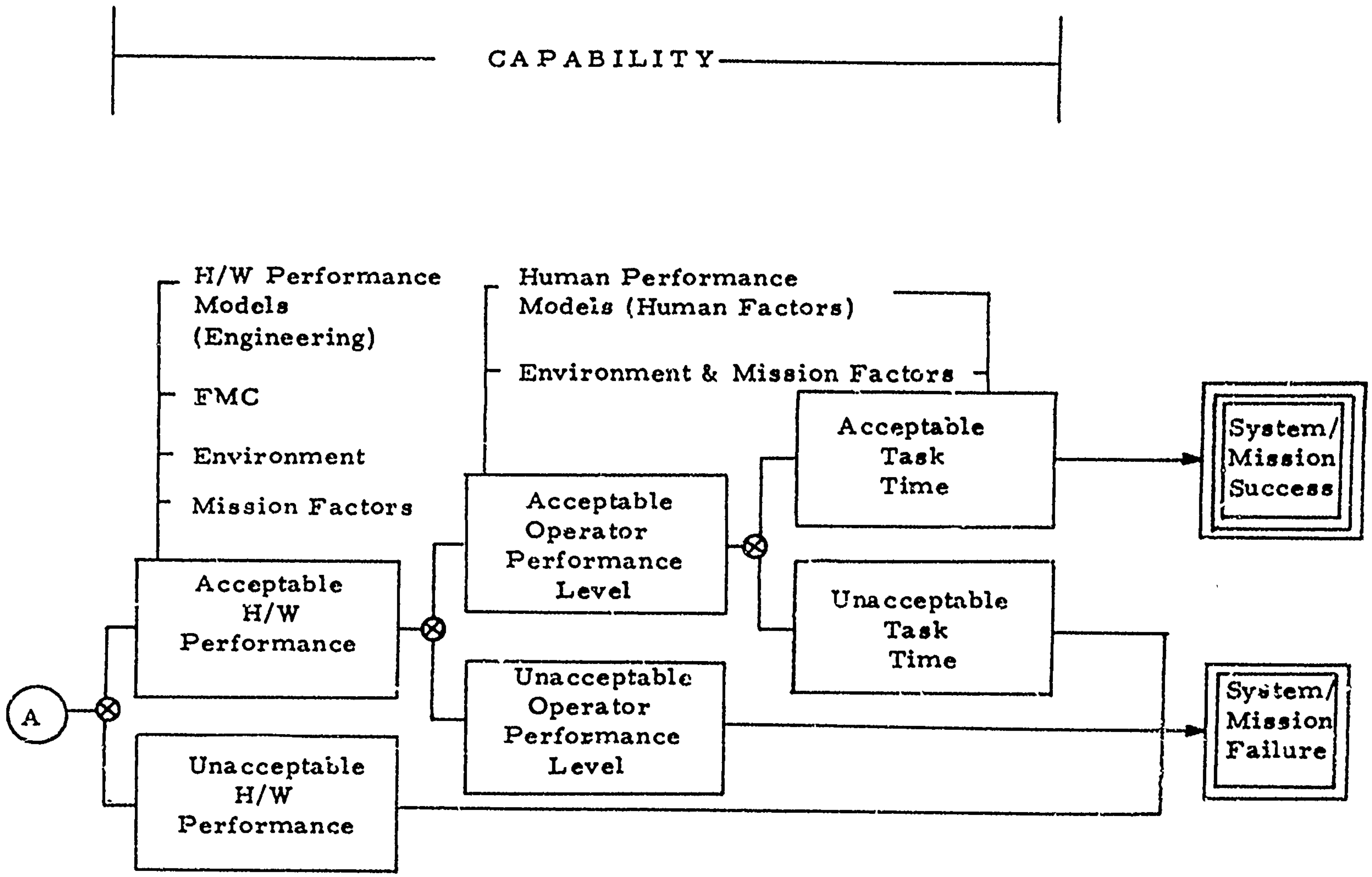

Figure 2-10. (Continued)

One of the major tools of the reliability analyst is the reliability block diagram. This is a block diagram of the system defining the series and parallel structure of the system elements, and forms the graphic basis for the mathematical model (reliability model) which states the probability of system failure during missions of stated duration. Since each element must have a defined failure rate, prediction data and methods are essential. Various compendia of such data are available and are continually updated through industry- and service-wide laboratory and field data collection programs. System function and mission analyses are also essential to obtain utilization factors (function "on" time), and detailed failure modes and effects analyses are further required to establish the relation between parts failures and consequences to mission success.

When predicted reliability is unsatisfactory, it is the responsibility of the reliability function to recommend cost-effective reliability improvement techniques which will enable goals to be achieved. Typically, these include the use of redundancy, parts selection and screening, derating, cooling and special designs. It is essential that this be done as part of the overall effectiveness program in order to guarantee that the relevant trade-offs with other system attributes are accomplished. In an ideal program, the design function of the reliability organization alternates with the modeling/evaluation function which is carried out in concert with maintainability, logistics, human factors, etc., within an overall system effectiveness analysis function.

2.4.2 Maintainability (M)

MIL-STD-721B defines Maintainability as "A characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources." This is distinguished from maintenance, which is defined as "All actions necessary for retaining an item in or restoring it to a specified condition."

Maintainability is also well-established as an effectiveness discipline through the relation of one of its major parameters, MTTR, to Availability and Dependability -- as discussed earlier. In engineering programs, the maintainability function must work closely with the reliability function within an effectiveness analysis framework

to establish the optimal levels of system reliability and maintainability, e.g., reliability/maintainability/availability (R/M/A) analysis is carried out to establish the most cost-effective combination of maintainability (MTTR) and reliability (MTBF) design features which meets the requirements for system Availability and Dependability. The opportunity for trade-off between the two functions is apparent in the $A = MTBF/(MTBF + MTTR)$ formulation of Availability as well as in the illustrative equations for Dependability given in Figure 2-7.

Typical maintainability activities include modeling, prediction, allocation, test/evaluation, maintenance concept and M design specification, design review and other activities necessary to provide assurance that the system's maintainability characteristics are consistent with system effectiveness goals. Since the repair time of a system depends on (1) failure characteristics, (2) detail design features such as packaging, labeling, test points, etc., and (3) maintenance technician characteristics, the maintainability function overlaps those of several other functions including reliability, human factors and logistics, with which close liaison must be maintained. In fact, it is not uncommon to find similar requirements for analysis and design criteria related to the maintenance features of the system in the specifications and standards for human factors, maintainability and logistics support -- all called out for the same acquisition program.

As with reliability, the maintainability organization alternates between a design function, and an analysis/evaluation function which is carried out within the system effectiveness analysis program. When predictions indicate unacceptable levels of maintainability, it is the responsibility of the maintainability design function to recommend maintainability design approaches which will enable goals to be met. In addition to detail design recommendations involving test-point levels, marking/labeling, packaging, accessibility and various "human engineering" criteria which are well-documented in "M Criteria handbooks," trade-offs and other analyses are used to establish maintenance concepts -- generally in cooperation with or as part of the Integrated Logistics Support function. The types of maintenance concept decisions made on the basis of modeling and analysis include: repair vs. discard of failed modules; location of module or equipment repair (shipboard, tender, depot, contractor, etc.); test point location; type and location of failure detection devices and test equipment (manual vs. automatic, special vs. general, built-in vs. portable, etc.); technician numbers and skill levels; special support equipment, tools and jigs; location and types of maintenance data and instructions; level of modularization and degree

of standardization; etc. Since these decisions have considerable impact on both effectiveness and cost, it is essential that the alternative maintenance concepts be evaluated within an overall cost-effectiveness context through exercise of the overall cost and system effectiveness models wherever possible. At minimum, suboptimization through lower-level trade-off analyses is required. A number of such trade-off models have been formulated and applied successfully.

2.4.3 Logistic Support

Shortages of spares and delays in obtaining spares, technicians, tools, support equipment, data and other supporting elements, are responsible for the major share of system downtime in many operational systems. Recalling the relationship of the mean downtime (MDT) term to Operational Availability and Dependability, it can be seen that logistic support is a major determiner of the realized or operational system effectiveness. Through maintenance engineering analysis (MEA) and the development of plans for maintenance (PFM) including the specification of spares levels and locations, maintenance manning, maintenance policies, etc., the logistics support function establishes the support system design through use of the effectiveness disciplines. In most systems, effectiveness is highly sensitive to the support system design, as is life cycle cost. Accordingly, older-style logistic support activities, which provided "after-the-fact" spares lists and support equipment designs, have been supplanted by the more-sophisticated Integrated Logistics Support (ILS) function.

ILS, when fully implemented, is a system engineering function performed throughout a system's life cycle which concerns itself not only with the support system design, but also with the inherent supportability of the system being supported. According to SECNAVINST 4000.29, "Development of Integrated Logistic Support for Systems and Equipments," ILS requires the "Coordinated and systematic planning, design, acquisition, distribution and management of the following major elements of logistic support as an integrated whole: (1) planned maintenance; (2) support personnel; (3) technical data and pubs; (4) support equipment; (5) spares and repair parts; (6) facilities; (7) contract maintenance." Since the concept of ILS is based on the "systematic interrelation of the actions required to obtain maximum material readiness and optimum cost effectiveness," and involves the "optimization of total-life cost of the system or equipment through analyses of potential trade-offs between reliability and maintainability requirements, and

alternative logistic support methods," it readily assumes a major and well-defined role within the system engineering program. In accordance with Navy policy set forth by SECNAVINST 4000.29, "Instructions issued by addressees pertaining to the major elements of logistic support and to related subjects such as configuration control, maintenance engineering, systems effectiveness, maintainability, and reliability shall recognize and support the concept of integrated logistic support." The ILS function is supported by the system effectiveness analysis function, which provides the essential analytic framework for making rational logistic support decisions within an overall operational context.

2.4.4 Human Factors (HF)/Human Engineering (HE)

MIL-STD-721B defines Human Factors as "A body of scientific facts about human characteristics. The term covers all biomedical and psychosocial considerations; it includes, but is not limited to, principles and applications in the areas of human engineering, personnel selection, training, life support, job performance aids, and human performance evaluation." Human Engineering is defined as "The area of human factors which applies scientific knowledge to the design of items to achieve effective man-machine integration and utilization."

Except for rare cases, Navy systems are man-machine systems. The role of the human factor in determining a system's Availability, Dependability and Capability was discussed earlier, and can often be of major significance in a system's achievable effectiveness. Even so, the weakness of many system engineering and effectiveness efforts is the failure to integrate human factors considerations into the overall effectiveness formulation. This is because the human factor is often difficult to assess quantitatively in a form which is readily introduced into a system effectiveness model. However, recent advances in human performance quantification and modeling have improved this situation.

Some of the functions which come under the general heading of Human Factors include human engineering requirements determination, man-machine function analysis, task and time line analysis, human engineering design of equipment, human performance reliability modeling and prediction, workplace layout, man-machine allocation of functions, personnel training and selection, manning, habitability, "personnel subsystem" test and evaluation, and related activities such as

design of operator and maintenance manuals and procedures, safety, etc.

2.4.5 Safety

MIL-STD-721B defines Safety as "The conservation of human life and its effectiveness, and the prevention of damage to items, consistent with mission requirements."

System safety analysis is carried out as an integral part of a system effectiveness program and involves the systematic identification of hazards which can arise during normal operations or as a result of hardware or personnel failures. As indicated in Figure 2-6, unsafe conditions may affect both Operator and Hardware Availability and Dependability. The system safety analytic process starts with hazard analyses to identify and evaluate hazards, formulates actions to eliminate or control hazards through modification of system elements or procedures, and feeds these actions into the effectiveness evaluation process to determine their impact.

One of the tools of safety analysis is the fault-tree. Starting with accidents defined by a preliminary gross hazard analysis, the analyst works backward to diagram contributory causes in the form of a tree with causative paths as branches. Each critical path points to independent causal elements called subevents for subsequent action. In order to have maximum usefulness in a system effectiveness program, the analyses should be quantitative and the probabilities associated with alternative possibilities should be defined together with uncertainties associated with input data.

Inputs to safety analysis include reliability failure-rate data, human reliability data (human error rates), failure modes and effects and other risk data derived in a mission context. Thus, it can be seen that a close relationship must exist between the safety function and reliability, human factors and the other effectiveness disciplines.

2.4.6 Vulnerability/Survivability

Vulnerability/Survivability in a system subject to enemy action is related to Availability and Dependability and probability of mission success in a way which is analogous to reliability and maintainability,

although in a somewhat more-complex way since interaction with the Capability term may exist. Generally, Vulnerability/Survivability requires a "war-game" type of approach involving both system performance and mission profiles including tactical threats. It may also be necessary to define Vulnerability arising from inherent failures and downtime as well, and some applications can become complex, requiring extensive simulation. However, whether simple or complex, the output essentially provides, under given conditions, the probability that various system functions are vulnerable to enemy action and, given such vulnerability, the probability that the function will survive, i.e., will continue to be performed within system specifications or, if damaged, will be restored within some critical period.

One of the more-important trade-offs is between Vulnerability/Survivability and performance. For instance, additional armor increases weight and decreases vehicle maneuverability but may improve survivability given a "hit." On the other hand, less armor increases maneuverability which may decrease the probability of "hit" but decreases survivability if it <u>is</u> hit. The objective is to achieve the design which balances these factors in such a way that the required system effectiveness is achieved and system value is maximized. Similarly, centralization versus decentralization has cost, performance and reliability versus vulnerability implications.

Other problems which arise include the optimal placement of equipments within a ship or facility with limited space when locations vary in vulnerability and equipments vary in mission-criticality; the optimal amount of self-defense, including ECM, as opposed to other capabilities related to the major objectives of the system (e.g., self-defense systems may displace cargo capacity and have cost implications); etc. The optimal solution to such problems is best achieved through a system effectiveness and system value formulation which considers explicitly the interrelation of all the factors. This becomes clear when one considers the potential effects on each other of vulnerability/survivability, operators and maintenance personnel actions, equipment failures and downtime, availability of spares, function and subfunction redundancies, and numerous other factors.

2.4.7 Electromagnetic Compatibility (EMC)

Electromagnetic Compatibility has been defined in Department of Defense Instruction 3222.3 of July 1967 as "the ability of communications-electronic (C-E) equipment, subsystems and systems to operate

in their intended environments without suffering or causing unacceptable degradation because of unintentional electromagnetic radiation of response." Furthermore, the instruction defines design compatibility as EMC achieved by the incorporation of engineering characteristics or features in all electromagnetic radiating and receiving equipment (including antennas) in order to eliminate or reject undesired signals, either self generated or external, and enhance operating capabilities in the presence of natural or man-made electromagnetic noise. The instruction goes on to define operational compatibility as EMC achieved by the application of C-E equipment flexibility to ensure interference-free operation in homogeneous or heterogeneous environments of C-E equipments. Operational compatibility involves the application of sound frequency management and clear concepts and doctrines to maximize operational effectiveness and relies heavily on initial achievement of design compatibility.*

According to MIL-E-6051D, "Electromagnetic Compatibility Requirements, Systems," an EMC system design program covers at least the following areas: (1) subsystem/equipment criticality categories, (2) degradation criteria, (3) interference and susceptibility control, (4) wiring and cable, (5) electrical power, (6) bonding and grounding, (7) lightning protection, (8) static electricity, (9) personnel hazards, (10) EM hazards to explosives and ordnance, (11) external environment, (12) suppression components.

The importance of EMC in system effectiveness is clearly apparent. To be properly related to the other factors and to determine its influence on achievable system effectiveness, quantitative measures are required. Generally, this requires that the effect of electrical/electromagnetic interference or other effects on system performance be predicted or measured within a mission context. and that the probabilities of total or partial interference with system functions be accounted for in the computation of system effectiveness. Depending on the type of effect, EMC may enter into the Availability, Dependability or Capability term -- or frequently in all three. If an EMC problem leads to total or temporary failure of a function, it can reasonably be accounted for in the Availability or Dependability terms depending on when it

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*Caine, S., "Electromagnetic Compatibility in Systems Effectiveness" in Proceedings of the NMC Fifth System Performance Effectiveness Conference, 1969.

occurs. If performance degradation rather than total failure occurs, it is probably easiest to account for in the Capability terms, although with some formulations (e.g., Eq. 2-4) it could be accounted for in the Dependability term as well.

CHAPTER THREE: SYSTEM EFFECTIVENESS IMPLEMENTATION

Within a systematic program of system/mission analysis, system engineering, integrated logistic support analysis, and test and evaluation, the system effectiveness approach is the key to rational generation of system requirements and to subsequent definition and development of systems. This is due to the following reasons:

(1) The criteria for system/mission success and failure are defined explicitly in terms of operational objectives.

(2) Formulation of the effectiveness model requires that system functions and quantitative system requirements be related to mission profiles and demands within realistic operational/environmental requirements and conditions.

(3) The inherent and extrinsic possibilities for system failure/degradation and restoration are related to the ability of the system to meet operational demands.

(4) Design characteristics, system/support-system configuration and operating/maintenance procedures are related to system/mission functional performance in such a way that detail design as well as major system alternatives can be evaluated in terms of quantitative impact on overall effectiveness.

(5) As a result of these attributes, a properly formulated system effectiveness model provides an essential tool in the system value approach for evaluating alternative approaches to system design/configuration, and thus provides the rational basis (1) for the iterative definition of systems in successively greater detail, (2) for the trade-off procedures required for system optimization and (3) for interpreting the results of test and evaluation. Thus, the effectiveness model provides the design-decision, evaluation capability, along with the cost model and considerations of military worth, required by the system analysis and engineering process.

The effectiveness model together with the associated definition of criteria and objectives plays a central role in the system analysis and engineering process in several ways. First, it provides the framework within which major alternative concepts are evaluated relative to each other and to operational objectives and missions. During and after selection of a concept, it provides the basis for quantitative development of system requirements and their allocation to subsystems and lower levels within the system hierarchy. Thus, effective communication between user and producer is promoted. Next, it provides the means whereby the producer can evaluate the developing system in terms of requirements to determine (1) whether the proposed designs/configurations are likely to meet operational (user) requirements, and (2) the need for, and effect of, design changes. It provides the framework within which test results can be evaluated by the user relative to operational requirements. And finally, the effectiveness model provides the basis for assessing system effectiveness during the deployment phase and thus aids in the continuing process of defining the requirements for system improvement, growth and eventual obsolescence in terms of changing threats and state of the art.

System effectiveness/system value (SE/SV) analysis is required whenever the selection of alternative designs, policies or plans is required, or whenever optimization of a set of continuous parameter values must be performed, on the basis of effectiveness or system value. SE/SV analysis, at an appropriate level, is an integral part of each evaluation step in the system engineering process and is thus required during each iteration until the design/development process is completed. SE/SV analysis is also an integral part of the integrated logistic support process, which is itself part of the system engineering process during the first three acquisition phases, and is required to evaluate the impact on system effectiveness and system value of support system alternatives. Thus, the SE/SV analysis approach and the SE/SV models are the decision tools of choice for use throughout the acquisition life cycle and provide a rational basis for decisions which must be made by system engineering and ILS managers.

Ideally, the iterative process of system development employs a basic algorithm more or less like the one shown in Figure 3-1. (1) Requirements/objectives at any level of system definition are used to guide (2) conceptualization and characterization of one or more approaches to satisfying the requirements/objectives. This provides a structure within which (3) criteria/measures and decision rules can

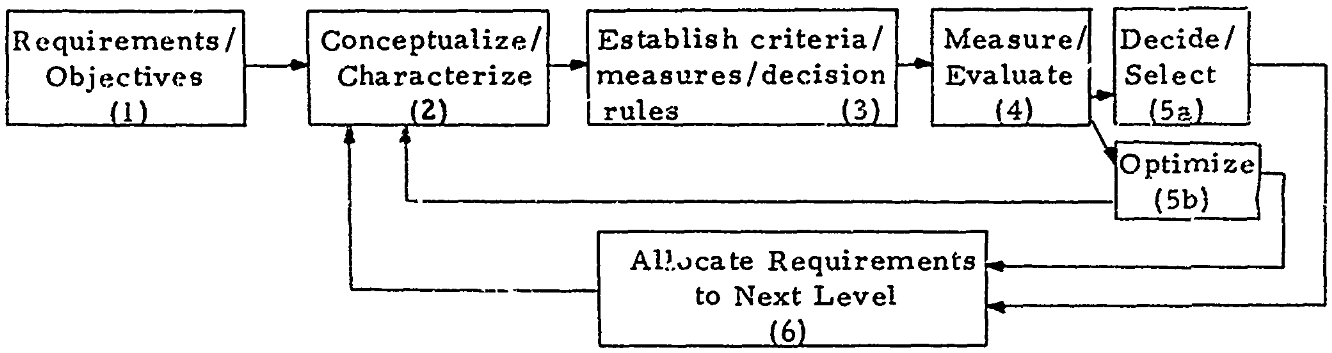

Figure 3-1. Idealized process for iterative system development

be established by which it can be decided whether or not the requirements/objectives are satisfied. (4) Measurement and evaluation (including modeling, prediction, model exercise, etc.) provide the basis either for (5a) a decision among alternatives if they are discretely definable or (5b) optimization in case of a continuous range of possibilities. This establishes the system's definition at a given level after which requirements are allocated to the next level of definition and the process is reiterated.

In system engineering, steps (1), (3), (4), (5) and (6) are cooperative activities of the design and analysis functions, with analysis taking the lead, whereas step (2) is almost entirely a design function. In practice, the design engineering groups and the specialty groups such as reliability, maintainability, logistics, human factors, etc., have both design and analysis functions. The design functions are collectively designated the "engineering" function within system engineering, while the analysis functions are collectively designated the "system analysis" function within system engineering and are coordinated among the various groups through use of the system effectiveness/system value approach. Thus, the design function is responsible for defining approaches to meeting effectiveness requirements, the analytic function evaluates the approaches using system effectiveness/system value models, and (ideally) both functions, through recommendations to management, participate in making decisions and allocating further requirements. Figure 3-2 translates this algorithm into a system-effectiveness/system-value engineering process.

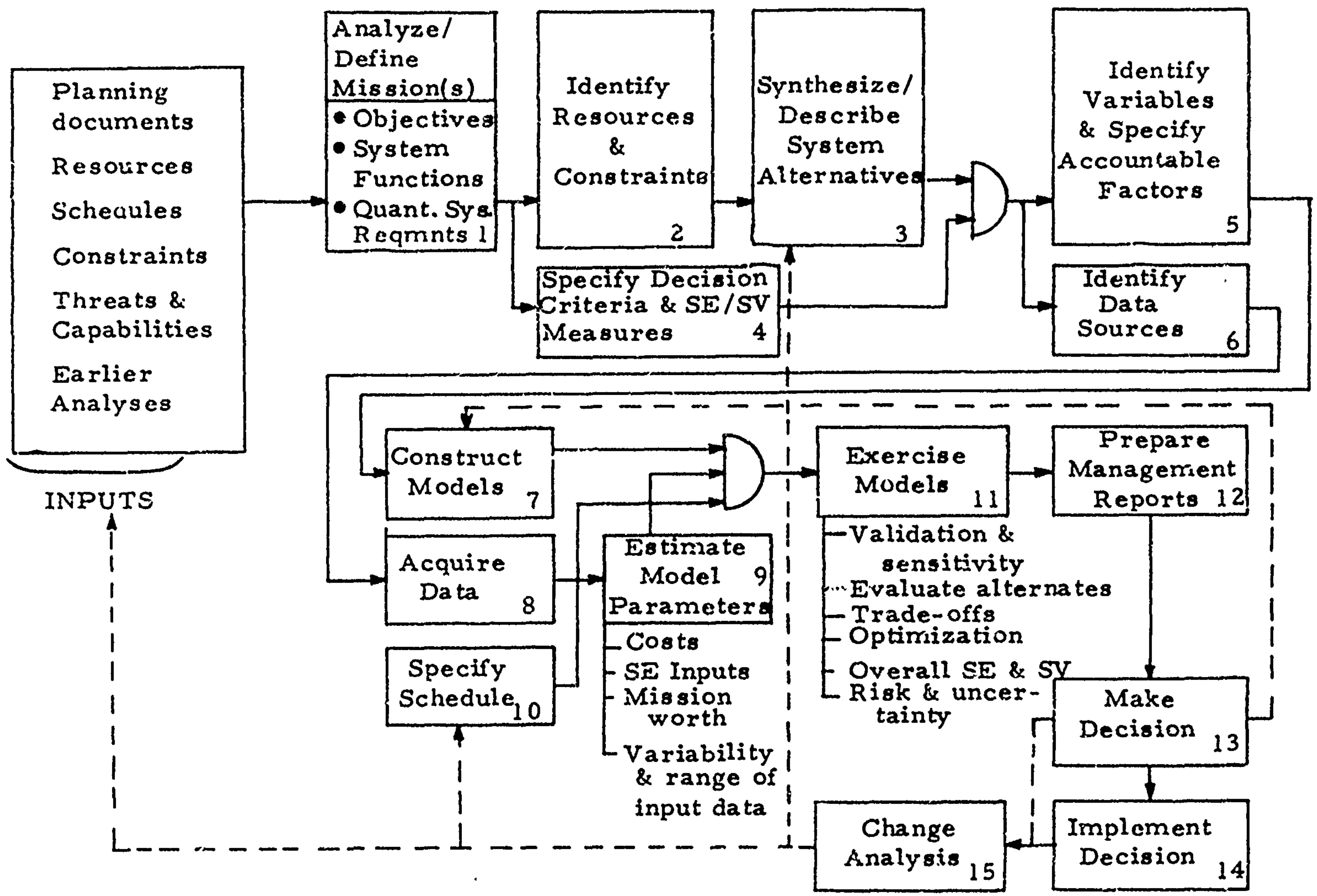

Figure 3-2. System Effectivenss/System Value Prediction/Decision/Implementation Cycle

Although the process is rarely seen in this ideal form in practice, it is nevertheless true that each step must be performed at least implicitly if systems are to be developed which are optimum in terms of mission objectives and effectiveness/value criteria. Significant curtailment of any of the critical steps (or their transposition, such as in "after-the-fact" analysis) will likely result in less than optimal systems or even in inability to meet operational requirements.

3.1 System Effectiveness/System Value Implementation Tasks

Implementation of the system effectiveness approach in a system program is aimed at producing the system with greatest value, hence this chapter considers effectiveness assurance within a system value context. Effectiveness is a measure of the ability of the system to accomplish the mission objectives. System value studies are concerned with achieving a combination of mission utilization, resource use and attained effectiveness that is best according to a selected criterion of value. Resource use represents the expenditure of dollars, manpower, material, time, facilities, etc., required for the development, operation and support of a system. Such studies are carried out concurrently and integrally with the development of missions and systems in order to select among a set of alternatives and to optimize the selected system.

System value extends the cost-effectiveness concept by considering the military worth of the primary and secondary missions of a system, thus taking into account differences in missions which can be performed by competing systems. If all systems being considered perform the same set of missions at the same rate and over the same duration, then for purposes of system selection, relative mission worth can be set at unity across all systems and the concept reduces to the familiar one of cost effectiveness.

There are four major decision-making levels at which system value analysis can be meaningfully applied. The first is to establish the mission(s) and objectives by considering overall defense goals, geopolitical and environmental factors, and economic and technological capabilities. This is generally coordinated at the DoD level.

The second is to synthesize alternative system concepts and to select the preferred system(s) during the Conceptual Phase. This is primarily the responsibility of the procuring agency.

The third is to optimize the preferred system to obtain optimal use of resources while satisfying system/mission requirements. This happens during the Validation and Full-Scale Development Phases and is the joint responsibility of procuring agencies and contractors.

The fourth is to monitor the operational effectiveness of the system and to provide the rationale for modification, improvement and eventual replacement. This happens during the Deployment and Operational Phase and is primarily the responsibility of the user.

This manual primarily addresses the second and third decision levels and the tasks required to implement the system effectiveness/system value approach. Typical implementation tasks and their interrelations are shown diagrammatically in Figure 3-2. The process is iterative and proceeds from gross to more-detailed levels along with the system engineering process of which it is part.

Task 1. Analyze/Define Mission(s)

System effectiveness/system value (SE/SV) analysis begins with definition and analysis of the mission(s) in order to derive or clarify objectives, system functions and quantitative system requirements. This should proceed systematically from identification of mission objectives and characterization of the threat to specification of mission segments and profiles, and result in mission scenarios with functional requirements, time lines and quantitative mission demands on system performance capabilities. Ideally, probability distributions of mission demands (performance levels, response times, durations, frequencies, etc.) should be derived. Derivation of a range of mission possibilities provides the basis for deriving system functions and quantitative system requirements along both performance level and time dimensions.

The mission definition task is critical to all the rest of the tasks, and is a prerequisite to specification of criteria and formulation of the effectiveness model. In too many projects, inadequate definition and analysis of the mission(s) results directly in poorly formulated criteria and unrealistic effectiveness models, and systems which are inadequately responsive to real operational requirements. This is particularly true for such factors as required response times which determine organizational configuration, maintenance and system ready policies; frequencies and durations of demand which have implications for reliability, maintainability, manning and spares; and other time-dependent factors. Inadequate consideration is also given to secondary or alternative

missions in many cases, resulting in a less-than-optimal system where a relatively small additional investment would have considerably extended the range of mission utilization and hence increased overall system value. Adequate mission definition and analysis identify these factors in advance so they can be reflected in system requirements, rather than waiting for their appearance in the field and the more-costly consequences of modification or simply living with the problem.

Task 2. Identify Resources and Constraints

In addition to defining the technical requirements of a system, it is also necessary to define the resources available for development and procurement, which primarily act as constraints and thus bound the system value model inputs. The four principal types of resources which must be considered are: budget, project manning, industry capacity and technology. In addition, time is a resource, and limitations on development time must be considered along with the change in military worth resulting from delays. This is generally governed by the phasing of other systems, and projections of threat, developing enemy capabilities, and growth in our own technology which may result in obsolescence of the current concept.

Other types of "constraints" are derived from mission considerations or as a result of model exercise and apportionment of goals/requirements to lower-level system elements. These are constraints on effectiveness variables or parameters (such as downtime, MTBF, etc.) or on lower-level cost elements resulting from analysis. These are derived rather than primary constraints and are part of Tasks 4, 7, 9 or 11.

The primary non-resource constraint (requirement) which is nevertheless primary and should be considered at this point is the minimum allowable effectiveness below which the mission and system could no longer be justified. This is a difficult determination to make in most instances unless a higher-level total force model was used to generate requirements, in which case the apportioned probability of mission success or system value index is consistent with that of other force elements. Frequently, however, setting a minimum effectiveness requirement is a matter of judgment. In either case, preliminary effectiveness requirements should be set at the highest organizational levels as a result of system value considerations and threat criticality, and included in early planning documents. If not, then the project

manager has no alternative but to set what he feels to be an achievable goal considering the state-of-the-art and gain approval after the fact. In any event effectiveness requirements should be set as soon as possible and included in the RFP for contractor guidance.

Task 3. Synthesize/Describe System Alternatives

In this task, objectives, system functions and quantitative system requirements are considered in synthesizing one or more system concepts or configurations. Resource constraints are used as bounds for screening and narrowing down the list of possibilities. The depth of system description depends on the phase of the system life cycle.

The number of alternatives identified depends on the available technology, budget and schedule. Practically speaking, alternatives should usually be limited to a few of the most-likely contenders. In some cases, only one basic system concept may be considered, and alternatives are considered only for lower-level system elements during the optimization process.

The level of system description depends on the phase of development, but should include at least the major attributes influencing effectiveness and cost. Any differences among alternatives in mission(s) utilization must also be included. Physical characteristics such as weight, volume, shape, energy levels, mechanical and electrical packaging and environmental capabilities should be included as well as performance characteristics such as accuracy, speed, range, capacity, power output, discrimination, etc. Depending on the phase of development, some level of definition of reliability, maintainability, human performance assumptions or capabilities, manning, maintenance concept and the like should also be included. In general, the major effectiveness factors of capability, availability and dependability should be kept in mind in order to generate a checklist of system functional attributes which will enable a model to be formulated on the basis of the mission and system description.

The Design Disclosure for Systems and Equipment (DDSE) discussed in Appendix B forms an ideal basis for system description in a form which is readily communicated to the system effectiveness analyst as well as to other program/project members.

Task 4. Specify Decision Criteria and SE/SV Measures

Concurrently with and immediately following Tasks 1 through 3, system, mission and resource definitions are analyzed in order to specify decision criteria and SE/SV measures. Actually, this is an iterative process since the nature of the criteria depends upon the level of consideration. The highest level criterion is system value, and the decision criterion may be expressed as "accept the system (or lower-level) alternative which has the highest value subject to the constraint that system value is equal to or greater than x with probability P. and that resource, effectiveness and other constraints are satisfied." In general, this is the preferred form for stating any criterion.

The first step is to identify the hierarchy of measures that correspond to important attributes of the system which influence value and its components -- system effectiveness, costs/penalties and military worth of missions. Some of the major factors were presented in Figure 2-1 for system value and in Figure 2-6 for system effectiveness. Having decided which measures are important, the processes of allocation (apportionment) and prediction are carried out. These accompany successive formulation and exercise of the SE/SV model(s) with each iteration at levels of increasing definition and provide quantitative specification of the required or apportioned values of the measures. Higher-level criteria or values of measures (requirements) come from mission and resource considerations. Lower-level criteria are derived by the joint use of prediction and apportionment. This proceeds as follows:

1. The system is defined at the next lower level.

2. Measures influencing value and effectiveness at that level are identified.

3. The SE/SV model(s) are formulated at that level.

4. Preliminary prediction of the quantitative values of the measures is carried out, or goals are allocated, for the system as defined.

5. The model is exercised to determine whether predicted or preliminary allocated values would be consistent with meeting higher level criteria with acceptable probability.

If so, these are established as the apportioned requirements at that level. If not, feasibility studies are performed to determine what measu[illegible] attributes) could be improved to meet higher-level criteria. These are then specified as the apportioned requirements and lead to modification of the system definition.

6. When the concurrent process of design (system definition) and analysis (evaluation) results in an agreed-upon system which, at the given level of definition, meets higher-level requirements, the process is taken to the next-lower level and repeated. However, decisions about criteria and measures at each level are regarded as tentative and subject to reiteration depending on the results of lower-level analyses. While lower-level analyses are performed on an element by element basis, they are finally used as input to the overall SE/SV model to determine whether apportioned criterion values are consistent with overall requirements.

The specification of decision criteria and SE/SV measures, then, is a dynamic, iterative process which evolves along with the system definition and SE/SV model(s) formulation and exercise.

Task 5. Identify Variables and Specify Accountable Factors

Each SE/SV measure at a given level is a function of primary and support system variables which must be interrelated within the framework of the model(s). Actually, the specification of measures and systematic examination of the system and mission will generally suggest these variables. Many of the variables become SE/SV "measures" or "criteria" at the next or lower levels of definition.

Specification of accountable factors is a management task which provides for the assignment of criteria/measures/variables, with stated quantitative design goals or requirements, to organizational entities. This suggests a natural basis for project organization which corresponds to program objectives, system definition and effectiveness tasks. It also provides the management control and visibility necessary for SE/SV assurance.

Task 6. Identify Data Sources

Specification of criteria, measures and variables also provides a specification of the type of data required as model input. Identification of sources for these data is a crucial and sometimes difficult task. Very frequently, alternative sources of varying quality exist, depending on the available budget and leadtime. The choice of source in such instances will depend on data criticality, which in turn is only verifiable through sensitivity analysis involving model exercise. Thus, initial specification of data source may need to be revised later.

Typical data sources include:

- Test and evaluation data
- Historical data from similar systems
- Field data collection systems
- Laboratory experiments using system mockups, simulators, etc.
- Computer simulation models
- Published "standard" data
- Subjective "expert" judgment data.

Data source selection will also depend on acquisition phase. For instance, early gross estimates may be satisfied by subjective judgments from "experts" and historical data from similar systems, while later estimates may, depending on sensitivity, require laboratory experiments or computer simulation, and finally, the use of T&E or field data.

A question which must always be answered is "what are the expected gains considering the cost of acquiring data from source x? " The major consideration in answering the question is the reduction in uncertainty related to data source improvement. Along a related dimension, the amount of such data to be collected determines the statistical factor of risk. The factors of risk and uncertainty must always be evaluated in specifying data source. The requirement is to relate (1) risk and uncertainty inherent in data, to (2) risk and uncertainty of decisions, to

(3) criticality of decisions to overall value and effectiveness. In other words, the "cost of being right" must be weighed against the "cost of being wrong."

Task 7. Construct Models

The tasks up to this point provide the basis for constructing the SE/SV model(s). The models to be constructed, of course, depend on what is to be done with them. In typical large-scale system programs, these uses will lead to construction of overall system value, system effectiveness and cost models. At lower levels, trade-off models are usually formulated for purposes of suboptimization since manipulation of the total model will generally be unwieldy and unnecessary for arriving at many decisions. Typical trade-offs include:

- Reliability vs. Maintainability
- Vulnerability/Survivability vs. Performance
- Safety vs. Performance
- Speed vs. Range
- Rate vs Accuracy
- Etc.

Trade-off models generally allow for the variation of two or more parameters (such as MTBF and MTTR) to determine the values which permit some objective to be met (such as availability) at least cost or penalty (where cost or penalty may be dollars, time, weight, manpower, etc.).

Either as a built-in feature of the model(s) or as a separate model, risk, uncertainty and their separate and combined effect on decisions should also be considered.

One of the decisions will be whether to construct special models or to use one of the general models which are available for some purposes. This will depend on budget, time and relevance of available

models. Relevance is determined by considering the properties of the model in relation to the system/mission in terms of the following qualities:

- Assumptions (reasonable?)
- Adequacy (includes all major variables?)
- Risk and Uncertainty (adequate treatment of probabilistic aspects?)
- Validity (has model been validated through actual use, i. e., does it yield field-verifiable outputs?)

Questions which should be answered about a model include:

- Consistency (are results consistent when major parameters are varied, especially to extremes?)
- Sensitivity (do input-variable changes result in output changes that are consistent with expectations?)
- Plausibility (are results plausible for special cases where prior information exists?)
- Criticality (do minor changes in assumptions result in major changes in the results?)
- Workability (does the model require inputs or computational capabilities that are not available or within the bounds of current technology?)
- Suitability (is the model consistent with the objectives, i. e., will it answer the right questions?)

Modern approaches to SE/SV and related modeling for military systems depend heavily on stochastic or probabilistic rather than deterministic formulations since they are to be used for making decisions under risk and uncertainty. Older deterministic models are therefore rarely adequate. Some of the available models and modeling approaches are discussed in the Appendices. The general characteristics of effectiveness models were discussed in Section 2. 2.

Task 8. Acquire Data

Early identification of variables and data sources should be made to allow sufficient time for data acquisition by the specialty groups responsible (reliability, maintainability, logistics, human factors, cost, performance engineering groups, etc.). Acquisition of data in computer input format will frequently expedite Task 9 (Estimate Model Parameters). Data should generally be collected in raw or semi-reduced form where multiple uses exist. This is particularly true for numerical data descriptive of stochastic processes characterized by probability distributions. In such cases, either raw data or, at minimum, the first four distribution moments (or distribution function) and sample size plus qualifications, data collection method, conditions or assumptions, should be reported. In the case of subjective "expert" judgments, estimates should be in the form of "high," "low" (or upper and lower percentiles) and "most likely" (or mean/mode/median) estimates, accompanied by qualifications of estimators, accompanying comments, their feelings of confidence, and methods/questionnaires/instructions accompanying the collection of the estimates. This is important for proper interpretation of the results and for arriving at estimates of "subjective probability distributions" and degree of uncertainty.

Data acquisition is followed by or concurrent with the next task.

Task 9. Estimate Model Parameters

Along with or following data acquisition, the values of model parameters to be input in Task 11 (Exercise Models) are estimated. Ideally, these should be in the form of probability distributions where the inherent process contains variability. Confidence intervals or sampling distributions should be associated with point estimates of means derived from samples, and "fiduciary limits" or "subjective confidence" associated with subjective estimates. These are discussed in Section 2.3.2.

Task 10. Specify Schedule

Specifying the schedule is a management task generally carried out with the aid of a PERT network or similar device. The main objective is to schedule design and analysis tasks so they are complementary and such that analytical results will have maximum impact on design. This almost always means getting the analytical/modeling tasks initiated

much earlier in the development cycle than has generally been the case in past programs. It is also necessary to schedule prerequisite analytical tasks such as Task 4, 5 and 6 with enough leadtime to provide timely inputs to the model formulation and exercise tasks.

Task 11. Exercise Models

In this task, the models are exercised to provide the inputs required by the decision process. If the models are well-formulated and data acquisition is successful, the models can be exercised in highly flexible ways in response to all the important questions requiring analytic resolution. In addition to overall estimates of system value, effectiveness and cost, numerous trade-off analyses and optimization studies will be available at the beck and call of project management and engineers. An important output for decision purposes will be the risks and uncertainties associated with each output together with important assumptions.

Prior to or concurrent with producing such outputs, the various parameters and variables should be varied over their ranges to determine sensitivity of the overall measures to variation in input values. This is an important indication of criticality of the associated system attributes, and is roughly a measure of the justifiable investment either in design activity, in quantification effort to reduce uncertainty, or in "over-design" to reduce risk.

Two principal uses of models are for evaluation and prediction. Evaluation provides:

- Surveillance of current system status against quantitative system requirements
- Feedback upon the efficacy of the management decision and program control process
- A means of determining system weaknesses or potential problem areas
- A point estimate of system value and effectiveness which includes all pertinent factors within a uniform framework.

Prediction provides decision aids through:

- Comparative prediction/evaluation of competing system configurations and problem solutions

- Calculations of the effects of risk and uncertainty expressed as confidence levels, parameter variation studies and changing requirements analysis.

The use of a model involves the following steps:

- Perform model checks

- Calculate values of criterion measures

- Do trade-offs within constraints

- Compare calculations with standard of reference

- Calculate parameter sensitivity curves

- Calculate risk

- Calculate effect of uncertainty

- Interpret runs.

Task 12. Prepare Management Reports

The results of model exercises (output values and risks/uncertainties) should be presented in summary form together with recommendations and important qualifications. The summary reports should be backed-up by more-detailed reports (separate or as appendices) which cover methods, model structure, assumptions, parameter values and summarized input data, etc. Where outputs have associated probability distributions, they should be plotted graphically so that management can readily choose a level of risk themselves rather than having the analyst's choice of risk implicit in the output. Accompanying these reports with disclosure in the DDSE format (see Appendix B) will considerably expedite interpretation.

Task 13. Make Decision

Although the analyst may make recommendations, the ultimate decision must rest with project management in order to reflect extra-analytic factors, which may in some instances be significant to eventual user-acceptance. However, a well-formulated and executed analysis will provide an ordered and rational basis for decision which should considerably enhance decision-making power and lend credibility which would otherwise be missing or difficult to provide.

Task 14. Implement Decision

Implementing decisions resulting from SE/SV analyses is similar to implementing decisions from design review or any other significant program event. Of course, without this step the point of the SE/SV analysis is lost. Nevertheless, this is frequently the weak point in system programs and results in much useless effort not to speak of a "bad taste" where analysis is concerned. Although the analyst can do much to encourage implementation through well-documented, well-formulated, relevant results, implementation depends ultimately upon the project manager and his understanding of the significance of the analyses and resulting recommendations/decisions.

Task 15. Change Analysis

The implementation of a decision based on SE/SV considerations implies a change in one or more of the following:

- Schedule
- Model(s)
- System definition
- Requirements (measures, criteria, etc.).

Each iteration should be accompanied by Change Analysis against each of these areas. The result will be a monitoring of the net effect of each decision and the accomplishment of program surveillance.

CHAPTER FOUR: SYSTEM EFFECTIVENESS IN THE RDT&E PROGRAM AND ACQUISITION CYCLE

The processes required to develop Navy systems are consistent and well-defined in basic terms although terminology, documentation and division into phases may vary from time to time. At any given time, the Navy RDT&E program is a structured procedure in which a continuous dialogue is maintained between the user (CNO/CMC) and the producer (CNM/contractors) from definition of broad objectives to system conceptualization, definition, development, production, deployment and operation. This process is summarized in Figures 4-1 and 4-2.

Figure 4-1 shows the normal documentation flow that takes place in the RDT&E planning process. The dialogue is continuous between the user and producer. It moves gradually and orderly from long-range planning on through the point of introducing new hardware and weapon systems to the men with our operating forces.

Figure 4-2 shows the major phases of the acquisition cycle in relation to RDT&E activities. Note the utilization of the DCP (Development Concept Paper) and DSARC (Defense Systems Acquisition Review Council) combination as a key for going into systems development and procurement. System Value with its components of System Effectiveness, Cost and Military Worth provide the key to these decisions from the earliest phases of the acquisition cycle. A key document related to this process is the DCP, which is a memorandum, issued by OSD, normally prepared by DDR&E, coordinated with the Services, expressing decisions on initiation of, or changes to, major R&D programs. A DCP is a relatively concise document (20 pages or less) which makes explicit assumptions concerning (1) agreed-upon problem or threat, (2) development time frame, (3) priority, (4) force levels contemplated and/or <u>measures of merit, or effectiveness, which will be used to evaluate and compare alternative or competitive systems</u>.* Thus, the "effectiveness approach" is initiated at the highest levels of the planning processes and at its onset. Continual development of the effectiveness

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*<u>Navy Research, Development, Test & Evaluation Program</u>, Headquarters, Naval Material Command, March 1972. See also <u>Department of the Navy RDT&E Management Guide</u>, NAVSO P-2457, 1 July 1972.

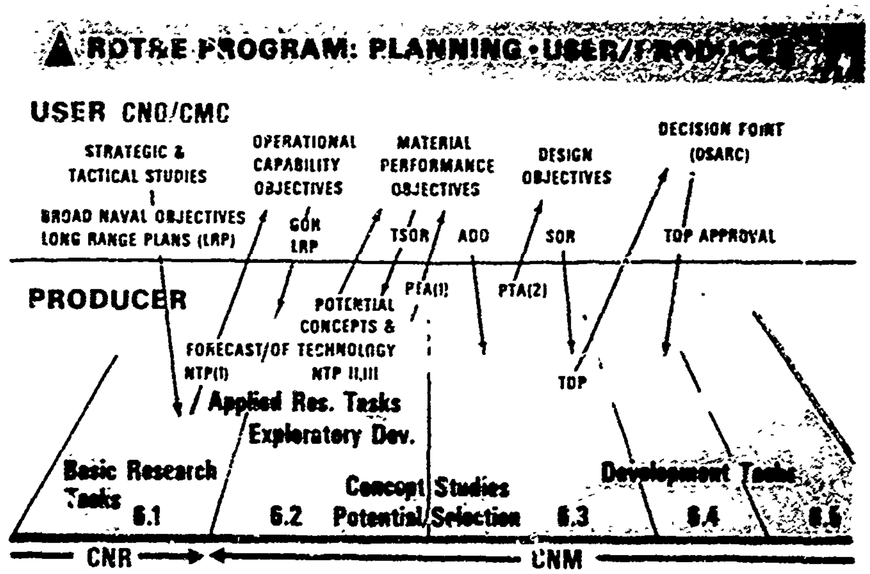

Figure 4-1. RDT&E Program: Planning, User/Producer Interaction

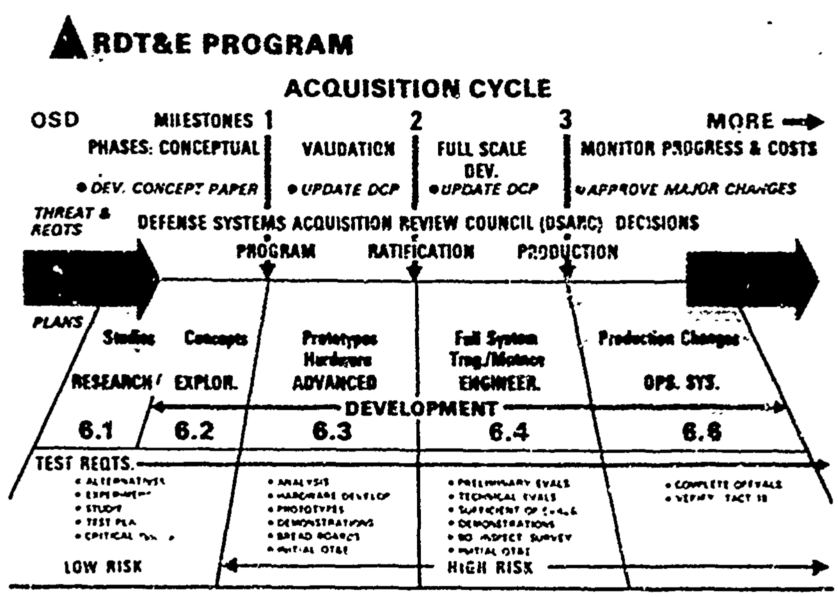

Figure 4-2. Acquisition cycle

model and its exercise for decision/evaluation throughout all phases are essential to successful execution of the RDT&E program.

4.1 The RDT&E Planning Dialogue

The user-producer relation is more analogous to a relation between cooperating independent business organizations than to traditional military relations. Plans are the result of negotiation between the two interests. Through this process trade-offs are made that will result in the maximum military capability for the operating forces within the limits of the resources available.

The principal documents used in the user-producer dialogue are shown in Figure 4-1. The process involves a continuous interaction between operational requirements and their spokesmen, and technical and scientific possibilities and their spokesmen. It is a continuing, iterative interchange.

The Chief of Naval Operations is responsible for the preparation of a General Operational Requirement (GOR) for each functional warfare and support area. GORs usually result from rather extensive long-range strategic and tactical studies. These documents state, in relatively broad but significant terms, the capabilities the Navy needs within each area. For guidance in making trade-offs in weapons design, the GOR should indicate the relative importance of the needed capabilities. In the past, performance capabilities have been adequately stated in the GORs; however, other considerations that constitute system effectiveness -- reliability, maintainability, etc. -- have not always been given adequate attention. System effectiveness guidance must be provided for the entire system at the GOR stage, for here, along with the evolving DCP, is where the thinking and planning for total system effectiveness begin.

In some cases the using agency issues a document concerning a narrower requirement, a Tentative Specific Operational Requirement (TSOR). This document states the need for achieving a particular operational capability and outlines the identifiable system characteristics necessary to fulfill the requirement. The TSOR defines the desired performance goals and provides additional information needed to weigh alternatives and make the tradeoffs required for an optimum system. The producer response to either the GOR or TSOR is a PTA (Proposed Technical Approach). PTAs are developed by the Naval Material Command to propose technically feasible alternative methods of accomplishing objectives set forth in a GOR or TSOR. The PTA should be

fully responsive to the GOR or TSOR; therefore, the quality of the PTA depends directly on the quality of the GOR or TSOR. In addition to other mandatory requirements of the PTA, the governing OPNAV and DoD directives require that the PTA analyze and compare the operational effectiveness of the proposed alternate development approaches in terms of performance, reliability, operability, and maintainability, and clearly indicate the basis of the comparison, such as previous experiments, extrapolation, or conjecture.

The user reviews what is presented in the PTA and decides on one of the following alternatives:

1. Study the requirement further

2. Begin feasibility studies, further experimentation, or both

3. Begin an engineering or operational development effort

4. Terminate development effort in the specific area

If alternative 1 is chosen, the process returns to the strategic and tactical study phase and usually results in revisions to the GOR or TSOR. If alternative 2 is chosen, the user interests develop and promulgate an Advanced Development Objective (ADO). If alternative 3 is chosen, the user interests develop and promulgate a Specific Operational Requirement (SOR). In the case of alternative 4, all effort proposed in the PTA is terminated, which usually results in the action indicated for alternative 1, although on occasion the requirement will remain unmodified and essentially dormant until research effort develops new technical approaches to be incorporated in a superseding PTA.

If alternative 2 (ADO) or alternative 3 (SOR) is chosen, the producer prepares a Technical Development Plan (TDP). However, there is a distinct difference between a TDP that responds to an ADO and one that responds to an SOR. In the case of an ADO, the effort defined by the TDP is either directed toward demonstration of feasibility of approach(es) or experimentation at the breadboard level. This effort, if successful, leads to an SOR and a responding TDP.

The TDP responding to an SOR represents the essential completion of the Conceptual Phase. The most important end product of the Conceptual Phase, it comprises the plan for fulfilling the operational

requirements of the user. The goal of a TDP is a balanced and integrated effort for optimizing operational effectiveness, total cost, and early availability.

With development of the TDP, the necessary RDT&E planning for subsequent phases of the system is established; if planning has been adequate, only a minimum of TDP updating will be required later.

4.2 System Effectiveness and the System Acquisition Process

The role of system effectiveness analysis during the acquisition process is to enable the program manager to restructure the allocated goals to the system level, thereby allowing system decisions to be made by higher management. The allocation process adds a new dimension to management. Dynamic life cycle management and Integrated Logistics Support then become practical goals. The vehicle for the structuring process is the system effectiveness model, frequently discussed but too often not used until after the fact.

The following sections describe the role of system effectiveness analysis in the system acquisition process. It will be seen that system effectiveness techniques are intended to aid the project manager in decision-making by presenting him with organized information, and to assist him in assigning task priorities by highlighting critical areas within his project. The discipline of System Effectiveness is not a replacement for managerial judgment; rather, it supplies a basis for better and more timely decisions.

4.2.1 Conceptual Phase

The Conceptual Phase includes the activities preceding a decision to carry out Validation (system definition/advanced development) and is conducted at the discretion of the Navy without specific approval by OSD. During this phase, the technical, military and economic bases for an acquisition program are established through comprehensive systems studies and experimental hardware development and evaluation. The Conceptual Phase is highly iterative. Its stages overlap rather than

occurring sequentially; however, flowing from interacting inputs of operational needs and technology, generally the following stages occur:

- Identification and definition of conceptual systems
- Analysis (threat, mission, effectiveness, feasibility, risk, cost, trade-offs, etc.)
- Experimentation and test (of operational requirements, key components, critical subsystems and marginal technology)

The outputs of the Conceptual Phase are alternative systems (including a preferred system) and their associated program characteristics (costs, schedules, and operational parameters) based on a combination of analyses, experiments and test results.

The initiation of successful system development programs in the U.S. Navy is becoming increasingly difficult in view of the rapid technological changes to be coped with and the growth of required program documentation. Success depends upon many complex factors such as the following:

- Determination of threat profiles and their translation into system requirements and constraints
- Status and understanding of performance parameters, resource estimates, and error budgets of exploratory/advanced development projects.
- Understanding of the activities required to satisfy the directives, requirements, and instructions of the DoD/Navy management system
- Availability of people, facilities, techniques, and data to support required activities.

The integration of the above factors, and others, for the specific purpose of initiating an engineering development program takes place during the Conceptual Phase. Much work has to be done to provide efficient conceptual capability. A cohesive marriage of the design and analysis techniques is required. The results of conceptual studies will have a major impact upon the cost and responsiveness of future Naval systems

4.2.1.1 Candidate System Definition

In an ideal situation the Conceptual Phase would progress from the recognition of a threat, to a number of approaches, to candidate concepts, and then to candidate systems. This idealized order is seldom realized. The lack of orderliness in the real-world evolution of the process can pose extreme problems if not approached in a disciplined manner.

Basic to a disciplined approach is the recognition that these stages of progress are simply differing degrees of precision in defining the system. In other words, the descriptive parameters become pro... ..sively better defined for each step in the evolution from approach to candidate system.

During the earlier stages, system functions are quite broadly defined. The gross functions are progressively structured as groups of subfunctions, each with its associated inputs and outputs. Structuring continues until the candidate system has been defined. This approach permits comparative evaluation of competing candidate systems, regardless of their relative stage of evolution.

4.2.1.2 Preferred System Selection

The preferred system selection process must take into account considerations other than system effectiveness. Among these are system value and risk. The cost analysis component of system value is based on two cost estimates associated with each function in the system effectiveness model. One estimate covers the cost of acquisition, the other covers the cost of utilization or ownership. The former includes the RDT&E costs, prorated over the anticipated production quantity, as well as the production and installation costs per system. The latter includes all operating, maintenance, and support costs of the system. These costs can be used in connection with trade-off analyses, or they can be aggregated and associated with the system value index and used as partial determinants in preferred system selection. Other partial determinants useful in preferred system selection are comparisons of system effectiveness indices with manpower and lead-time requirements.

Along with the formulation and exercise of the system value model and its submodels for effectiveness, cost, development time and the like, a formal analysis of risk and uncertainty should be initiated. This

requires that sources of risk and uncertainty associated with each input be identified and that estimates of the range, variability and/or confidence of inputs be made. These are then combined appropriately during the analysis to provide the combined risk and uncertainty due to all sources for each of the major parameters -- effectiveness, cost, development lead-time, etc. This provides a critical input to the system selection decision process, and may lead to an entirely different decision than would have been made without it. In addition to identification of sources of risk and uncertainty, a most useful form of output of an analysis of risk and uncertainty is a probability distribution (objective or subjective) of each measure or parameter. The project manager is thereby given a "quantitative" definition of risk and uncertainty in terms of the probability (under the stated assumptions) that time, cost or effectiveness will meet, exceed or fall short of requirements or goals -- and by how much. It is also a direct measure of the combined effects of the quality and/or variability of input data on any decisions made on the basis of exercising the models.

The results of the effort to this point are formally organized as a PTA and submitted through appropriate channels to the Chief of Naval Operations.

The system value methodology is based on the evaluation of system effectiveness, military worth, cost and their degradation as a function of the time to acquire the system and of operational life-span. Neither military worth nor degradation is directly measurable. However, they can be assigned numeric judgment valuations by military experts. The military worth index is an evaluation of the mission to be accomplished by the system. If all candidate systems accomplish identical missions, the military worth valuation can be set at unity, and only the effects of cost, time-to-acquire and operational life-span will be considered in the evaluation. On the other hand, if one or more of the candidate systems are capable of accomplishing additional missions or different combinations of missions, the indices of military worth should reflect the differences as military judgment may deem appropriate. The net effect of the system value methodology is to provide a military judgment coefficient to assist in system selection.

The actual selection is suggested by the candidate system with the highest index of system value. However, this suggestion is not absolute. Modeling assists in the decision-making process and is not a substitute for managerial judgment. Indeed, judgment may result in a decision at this stage that more than one preferred system will enter Validation.

Formal Conceptual Phase activity generally terminates with proposal of a "system option" in Part III of the Navy Technological Projections (NTP) or with the response to a Tentative Specific Operational Requirement (TSOR) and the issuance of an Advanced Development Objective (ADO). In practical application, then, the Conceptual Phase includes the early conception of new systems (which help provide focus for Exploratory Development planning) and the program execution required to provide the technology necessary to make the concept technically feasible.

The preferred system(s) having been selected, one step remains prior to Validation. To the project manager, this is one of the most critical steps, and his first major test as a manager. He must demonstrate that he has met all of the prerequisites to obtain DSARC review and SECDEF approval to enter into Validation.

If not approached in a well-organized manner, this demonstration can be a time-consuming and frustrating exercise. However, the System Effectiveness/System Value methodology, with the associated models, provides the ordered approach and the demonstration vehicle. Using these models, the manager can define the system(s) in terms of technical goals and criteria, trade-off evaluations, and priorities of effort, together with the associated confidence levels.

Application of the Navy system value methodology throughout the Conceptual Phase of the system's life cycle places the manager in an unambiguous position. If he can define his system sufficiently well to exercise the models, it is probable that his system is soundly conceived and that the model completion in itself will demonstrate his meeting of the prerequisites for Validation. On the other hand, inability to provide minimal input requirements for model analysis and/or to provide clear system definition is a strong indication that prerequisites have not been met. Having successfully demonstrated accomplishment of prerequisites during the Conceptual Phase, the manager uses the essential inputs to prepare the Request for Proposal (RFP) needed to cover the contracted effort.

4.2.2 Validation Phase

This is the phase in which the major program characteristics (technical, cost and schedule), through extensive analysis and hardware development, are validated and is often identified with Advanced Development. It is preferred to rely on hardware development and evaluation

rather than paper studies alone, since this provides a better definition of program characteristics, higher confidence that risks have been resolved or minimized and greater confidence in the ultimate outcome. Nevertheless, effectiveness analysis plays a critical role since it provides a structured vehicle for interrelating and evaluating the information developed as a result of hardware development, and organizes information in a form suitable for updating the DCP, and for DSARC review leading to the decision to enter Full Scale Development. In an idealized case, this phase ends when a "brass board" model has been demonstrated successfully.

The Validation Phase is a period of major concern to the project manager, although the burden of proving performance and responsiveness rests on the contractor (private industry or Government laboratory) who has been selected as a qualified participant essentially on the basis of proposals.

In many respects the application of the system value methodology to Validation parallels its application in the Conceptual Phase. There are, however, some significant differences. In time sequence, the application of the system value concept during the Conceptual Phase, as discussed in Section 4.2.1, is applicable if the term "Contractor's Proposed System" is used in lieu of "Candidate System."

The candidate and preferred system(s) having been defined in the Conceptual Phase, a sensitivity analysis is performed with the effectiveness model. This analysis will indicate the limiting parameters and priorities for each element of the system model, which are expressed in terms of technical goals or requirements. The range of the permissible parameters, properly related to estimates of state-of-the-art capabilities, establishes the degree of criticality of the element.

Along with the sensitivity analysis, the analysis of risk and uncertainty performed during the Conceptual Phase should be updated, extended and carried out to greater levels of detail.

The system(s) definition and the critical system effectiveness parameters are incorporated into a Request for Proposal, which is transmitted to the contractor(s) as a guide for proposed approaches to Validation. The system(s) definition provides for the initiation of Validation, the equivalent of Candidate System Definition in the Conceptual Phase. In addition to guidance for the contractor(s), the definition of critical system effectiveness parameters provides the criteria for evaluating contractor proposals.

As with other aspects of the system effectiveness discipline, the definition of critical system effectiveness parameters is not static. The process of refinement started in the Conceptual Phase continues in Validation. As a result of the analysis of contractor or laboratory proposals, the system(s) definition is refined, and the critical parameters are better defined by the inputs received from the responses to the RFP. This sharpening becomes most important to the project manager during latter stages of Validation and during Full-Scale Development

The project manager may exercise little control over the Validation effort. However, progress reports under the contracts do provide definition and validating data. As these data are received, reiterative exercise of the system effectiveness model provides a significant measure of the progress being realized.

While the critical system effectiveness parameters can be defined initially during the early Conceptual Phases, they reach much greater definition in the latter stages of Validation during the analysis effort. They provide the essential framework for the decision to enter into Full-Scale Development.

The definition of these parameters at this point in the evolutionary cycle of a system must be sharpened to the point where the project manager can demonstrate the following:

- The operational goals and technical goals are in agreement
- The technical, and hence operational, criteria can be met
- The financial and schedule factors are credible
- The development risks are acceptable
- A definitive Full-Scale Development contract can be entered into with the best-qualified contractor.

To demonstrate the foregoing, not only must the parameters be clearly and concisely defined, but they must be quantitatively interrelated. This requires highly structured system models in terms of functional block diagrams with associated characteristics values and a completely structured System Effectiveness/System Value model with

which to analyze and evaluate the system models. The former is an output of Validation contractor efforts. The latter, however, is largely the result of the efforts of the project manager's staff or research/analysis contractor. The success or failure of Validation will be determined by the degree of completeness of the model and the degree to which its structuring conforms to the real-world situation.

If the System Effectiveness/System Value model does approximate reality successfully, the parameters can be interrelated, and the exercise of the model for each of the competing systems produced by the contractor(s) provides a framework for source selection and demonstrates the validity of entering into Full-Scale Development, continuing with further definition or advanced development effort, or abandoning the project.

In addition to its use as a decision-making tool, the model also serves another function during this period. The sharply defined critical effectiveness parameters provide the checklist for completing the specification for Full-Scale Development. This is particularly important in that one of the principal objectives of the Validation process is to assure that a complete and unambiguous specification is developed for the Full-Scale Development effort.

4.2.3 Full-Scale Development

Through the process of Validation, the project manager has been establishing a frame of reference to define the system, its technical goals and criteria, and the measures by which its effectiveness in terms of its mission life costs can be evaluated. Having established this frame of reference, he must now address himself to obtaining assurance of achieving an effective system.

During Full-Scale Development, the weapon system including all of the items necessary for its support (training equipment, maintenance equipment, handbooks for operation and maintenance, etc.) is designed, fabricated and tested. The intended output is a "hardware model" whose effectiveness has been proven experimentally together with the documentation needed for inventory use. An essential activity of the development phase is test and evaluation, both that conducted by contractors and that conducted by the Service. Documentation of the Full-Scale Development Phase, including the results of effectiveness analysis, provides the basis for updating the DCP and convening DSARC leading to initiation of Production/Deployment.

The ultimate evaluation of the Full-Scale Development Phase occurs during the test and evaluation of the developed system. If the system model and system effectiveness analytic model are valid and adequately defined, the system should meet its test and evaluation successfully, and the project manager will have been successful.

If the system is not satisfactory, the models have yet another function. The data accumulated during T&E should be inserted into the models. The models should then be exercised and the results analyzed to identify problem areas. These should then be recorded and made available to other project managers to assist them in avoiding similar errors. At the same time, a closed-loop management system should be implemented to correct the problems.

If the project is to be continued, whether or not the T&E is successful, the T&E data are inserted in the models to sharpen further the definition of technical goals and criteria and to validate the data for the production baseline and production specification. Here, again, the models serve to guide the effort and to assure the project manager that the baseline (specification) is complete and defined as sharply as the aggregate experience will permit. This is a necessary exercise, whether or not the R&D contractor is also the initial production contractor.

4.2.4 Production Phase

When the system has passed the test and evaluation and has been approved for service use, the project manager must produce the system and introduce it into the operational forces. In the past, this transition from Research and Development to Production has meant turning the project over to a new team. all too frequently involving a great deal of learning for the new team, time losses, and a loss of experience and data.

Two factors could provide safeguards against these traditional difficulties. The first, the project-manager concept, includes provisions for keeping the management team intact. The same management team that was responsible for R&D should have some continuing responsibility for production. Thus the time loss involved in learning the system is eliminated. The second, use of both simulation and analytic models, provides a methodology for experience and data retention. The formal structuring and recording of data provide a high degree of assurance that both experience and data will be retained.

When viewed objectively, the demands placed on the project manager for changes in configuration, cost, and schedule differ little in concept from the trade-off analyses performed during the Conceptual or Validation Phases. Indeed, the same tools, the system model and the analytic models for effectiveness and value, can be used. Actually, since the model values have now been more sharply defined through the introduction of experimental data during Validation and Full-Scale Development, the validity of the models as decision-making aids should be very high.

4.2.5 Deployment Phase

An important function of system effectiveness during Fleet operations is the retrieval of data for future programs. One significant attempt to provide a portion of these data from operating units is the MDCS (Maintenance Data Collection System) carried out under the Navy 3M Program. Attempts should be made to structure the MDCS data formats in such a way that the requisite inputs to the system effectiveness model can be obtained from the MDCS without additional reporting requirements. The project manager would then have available to him the main body of field data, which could then be introduced into the models.

Other sources of data are also available, such as the Failure Rate Data (FARADA) Program which provides failure rate, failure mode, and test background data on both electrical and mechanical parts and components; and the Government-Industry Data Exchange Program (GIDEP), which was established in 1960 to minimize duplicate testing through the interchange of environmental test data and related technical information.

Field data are needed for two principal reasons:

- They provide the real-life validating information on the project manager's past decisions. Through this validation effort he can determine the adequacy of weighting and other judgment factors that were applied during the preceding phases. An added return is the recording and sharing of these evaluations with project managers for other systems under development or for superseding systems. In this application of the system effectiveness methodology, the Navy can receive substantial benefits in experience retention.

- These data can also be used to establish a decision baseline for determining the need for so-called product improvements in operating systems, and for evaluating proposed changes. Costly changes and changes of questionable return may result from use of inadequate or incomplete data.

In the operational phase, as in the preceding phases, the discipline of the system effectiveness approach guards against making decisions on the basis of inadequate, incomplete, or unrelated data -- principally through the visibility that modeling techniques give to the ramifications of the variations in data inputs. While the system effectiveness approach is by no means a panacea and certainly not a substitute for sound judgment, it does provide a structured discipline that substantially increases the probability that the project manager will have as inputs to deliberations the factors necessary to assure that he makes the right decisions.

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MIL-STD-499	Systems Engineering
MIL-STD-721B	Definition of Effectiveness Terms for Reliability, Maintainability, Human Factors and Safety
MIL-STD-756A	Reliability Prediction
MIL-STD-781B	Reliability Tests: Exponential Distribution
MIL-STD-785A	Requirements for Reliability Program
MIL-STD-881	Work Breakdown Structure for Defense Material Items
MIL-STD-882	System Safety Program for Systems and Associated Subsystems and Equipment: Requirements for

MIL-STD's	TITLE
MIL-STD-1326	Test Point Selection and Interface Requirements for Equipment Monitored by Shipboard On-Line Automatic Test Equipment
MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment and Facilities
MIL-E-6051	Electromagnetic Compatibility Requirements, Systems
MIL-H-46855	Human Engineering Requirements for Military Systems, Equipments and Facilities
MIL-M-24100A	Manuals, Orders and Other Technical Instructions for Equipment and Systems
MIL-HDBK's	
MIL-HDBK-217A	Reliability Stress and Failure Rate Data for Electronic Equipment
MIL-HDBK-226	Design Disclosure for Systems and Equipment
MIL-HDBK-472	Maintainability Prediction

GENERAL REFERENCES

Weapon System Effectiveness Industry Advisory Committee (WSEIAC)

AFSC-TR-65-1	Final Report of Task Group I "Requirements Methodology"
AFSC-TR-65-2	Final Report of Task Group II "Prediction - Measurement"
AFSC-TR-65-3	Final Report of Task Group III "Data Collection and Management Reports"
AFSC-TR-65-4	Final Report of Task Group IV "Cost - Effectiveness Optimization"
AFSC-TR-65-5	Final Report of Task Group V "Management Systems"
AFSC-TR-65-6	Final Summary Report "Chairman's Final Report"

PERIODICALS RELATING TO SYSTEM EFFECTIVENESS

Annals of Reliability and Maintainability

Defense Industry Bulletin

Defense Management Journal

Engineering Cybernetics

Engineering Economist

Human Factors

IEEE Transactions on Computers

IEEE Transactions on Parts, Hybrids & Packaging

IEEE Transactions on Reliability

Innovation

International Journal of Systems Science

Journal of Optimization Theory & Application

Journal of Systems Management

Journal of Systems Engineering

Management Science

Management of Personnel Quarterly

Microelectronics & Reliability

Naval Research Logistics Quarterly

Naval Research Review

Naval Ship Systems Command Technical News

Operations Research Quarterly

Operations Research

Proceedings, Annual Symposium on Reliability

Proceedings of the Naval Material Command

Quality Progress

Systems · Computers · Controls

Systems Performance Effectiveness Conference (1965-1969)

Technometrics

Theory of Probability and its Applications

ORGANIZATIONS

Naval Electronics Laboratory Center
Product Assurance Division (Code 4100)
San Diego, California 92152
Autovon 952-6389 or (714) 225-6389

Naval Material Command, System Performance
Effectiveness Steering Committee
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Naval Ship Engineering Center (Code 6173)
Hyattsville, Maryland 20782
Autovon 296-1633 or (202) 436-1633

Naval Air Systems Command
Systems Effectiveness Branch (NAVAIR 5205)
Washington, D.C. 20360
Autovon 222-7596 or (202) OX 2-7596

Naval Electronic Systems Command
Systems Effectiveness Engineering Division (047)
Washington, D.C. 20360
Autovon 222-3877 or (202) OX 2-3877

Naval Ordnance Systems Command
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Washington, D.C. 20360
Autovon 222-8163 or (202) OX 2-8163

Naval Ship Engineering Center
Systems Effectiveness Section (NAVSEC 6181B)
Hyattsville, Maryland 20782
Autovon 296-1561 or (301) 436-1561

Naval Ship Systems Command
Electronics Support Section (SHIPS 03526)
Washington, D.C. 20360
Autovon 222-1194 or (202) OX 2-1194

Naval Material Command
Reliability and Maintainability Office (NAVMAT 09H)
Washington, D.C. 20360
Autovon 222-1106 or (202) OX 2-1106

ELECTRONIC INDUSTRY ASSOCIATION

(1) Proceedings of the First EIA Conference on Systems Effectiveness (1965)

(2) Proceedings of the Second Systems Effectiveness Conference (1967)

(3) Proceedings of the EIA Systems Effectiveness Workshop (1968)

(4) Effectiveness Quantification Bulletins

Number 1 - System Performance Models

Number 2 - Integration Engineering for Systems Effectiveness

Number 3 - Support System Analysis

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APPENDIX A

AN ILLUSTRATIVE EFFECTIVENESS MODEL AND COMPUTATION

Suppose a mission demand which may occur at any random point in time requires that a system be available within 0.25 hours to perform two tasks, A and B, in sequence within a combined accuracy, θ, of 0.90 or better; that no more than one failure may occur after mission start with resultant downtime, t_R, not exceeding 0.5 hours; that the total task time (excluding restore time during the mission) may not exceed t_M hours; and that failure to meet any of these criteria results in failure of the system to meet mission objectives. The various alternatives are diagrammed in Figure A-1 in a form which simplifies the task of formulating a system effectiveness model. Failure and success paths are shown with system states and tasks in relation to them. To formulate the model, expressions or estimates must be derived for (1) conditional probabilities at the defined branching points; (2) probability distributions of restore and task times; (3) the probability distributions of task accuracy; and (4) the mission time, t_M (or its distribution if it is variable).

At this point, it should be noted that constructing a diagram like Figure A-1 requires mission/threat analysis in order to define the criteria. These criteria (effectiveness criteria) define the conditions for mission success and failure, which in this case are summarized as follows:

(1) The system must be available within 0.25 hours after warning

(2) Only one failure is allowable during the mission

(3) If a failure occurs, downtime during the mission must not exceed 0.5 hours

(4) Tasks A and B must be performed with an accuracy of 0.90 or better

(5) Total task time must not exceed t_M hours (in this illustration, t_M is taken to be the mission time).

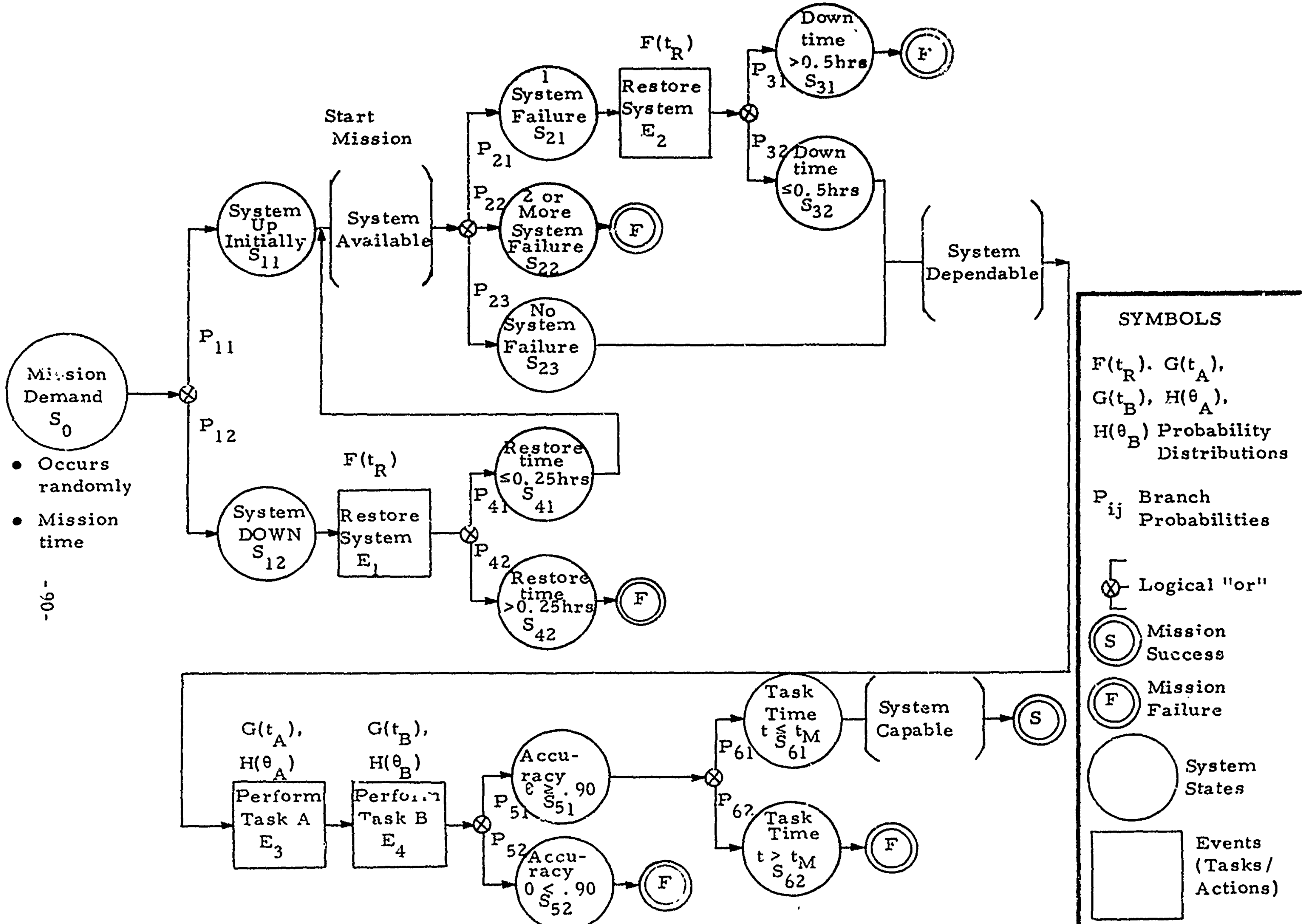

Figure A-1. Illustrative system state diagram (ESN - Event Sequence Network)

In addition to these criteria, mission/threat analysis provides the basis for two other vital bits of information:

(6) Mission demands occur randomly

(7) Mission time (duration of demand or time allowed to achieve mission objectives) is t_M. For this illustration it is assumed that t_M is constant.

System effectiveness in this case is simply the probability of mission success. Accounting for all the ways the mission can succeed, then, is an essential first step in formulating the SE model with the help of Figure A-1. The first step is to convert the system state diagram (also called an ESN, or Event Sequence Network) into a branching tree diagram such as the one given in Figure A-2. In Figure A-2, it can be seen that two major branches occur after S_0: the branch leading from S_{12} (state 12) on the left has 7 failure paths and 2 success paths; the branch leading from S_{11} on the right has 6 failure paths and 2 success paths -- a total of 13 failure and 4 success paths. The next modeling task, then, is to write the overall expression for S_E, which is the probability of being on any of the 4 success paths. In order to do this, the modeler uses two properties of probability trees:

(1) Given that the initial state (S_0) occurs, the probability of ending up at any given end state (success or failure) is obtained by multiplying all the intervening state-probabilities along the path from S_0 to the end state.

(2) The sum of the probabilities of all end states equals 1 (unity); and the total probability of success is the sum of the probabilities of all success end states.

Using these properties, system effectiveness in this case is simply

$$S_E = \text{Pr. Success} = P_{12}P_{41}P_{21}P_{51}P_{61} + P_{12}P_{41}P_{23}P_{51}P_{61}$$

$$+ P_{11}P_{21}P_{32}P_{51}P_{61} + P_{11}P_{23}P_{51}P_{61}.$$

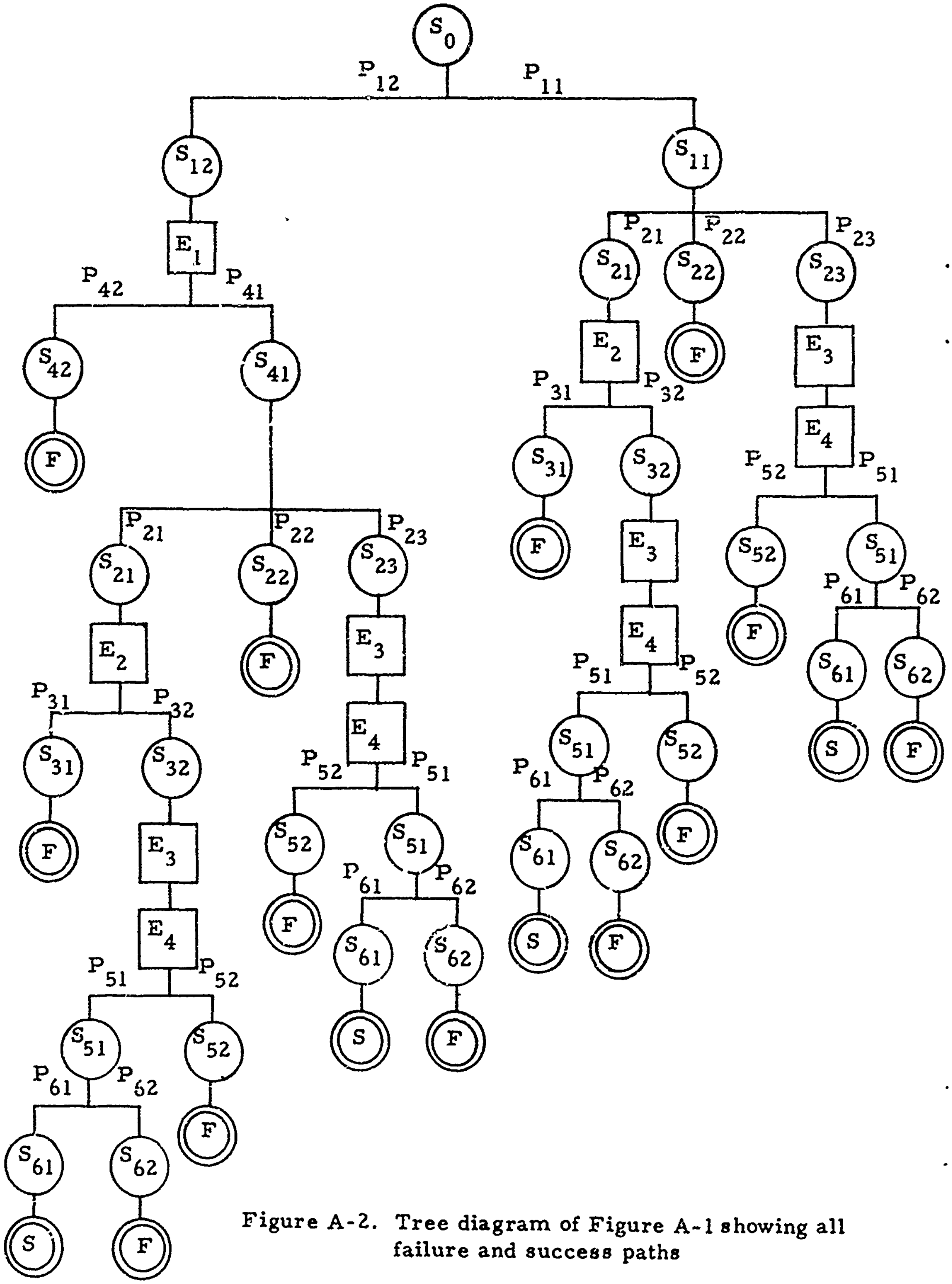

Figure A-2. Tree diagram of Figure A-1 showing all failure and success paths

Collecting terms, this becomes

$$S_E = (P_{12}P_{41} + P_{11})[P_{51}P_{61}(P_{21}P_{32} + P_{23})]. \qquad \text{Equation A-1}$$

It is not necessary, for present purposes, to define the failure states since

$$\text{Pr. Failure} = 1 - \text{Pr. Success.}$$

The next task is to estimate or derive expressions for the state probabilities P_{11}, P_{12}, P_{21}, P_{23}, P_{32}, P_{41}, P_{51} and P_{61}. This may be accomplished by referring back to Figure A-1, which states the necessary criteria, and proceeding as follows:

<u>P_{11} (Pr. of System UP Initially)</u>

Since mission demands occur randomly, this is the probability of the system being up at any random point in time, which was defined earlier as Availability. If for simplicity we assume technicians, operators, spares, etc., are available immediately, then

$$P_{11} = A_i = \frac{MTBF}{MTBF + MTTR}.$$

Suppose reliability prediction indicates that times between failures are distributed exponentially (constant failure rate) with a mean time between failures, MTBF, of 100 hours; and maintainability prediction indicates that repair time is distributed lognormally with a mean time to repair, MTTR, of 0.50 hours. Then

$$P_{11} = A_i = \frac{MTBF}{MTBF + MTTR} = \frac{100}{100 + 0.50} = 0.9950.$$

P_{12} (Pr. of System DOWN Initially)

The conditional probabilities at any juncture add to 1, i.e., the system is either up or down initially. Since $P_{11} + P_{12} = 1$, then

$$P_{12} = 1 - P_{11} = 1 - 0.9950 = 0.0050.$$

P_{21} (Pr. of One System Failure During Mission)

Assume an exponential failure density, i.e., constant failure rate, λ, where $\lambda = 1/\text{MTBF}$. The number, $\underline{i}$, of failures occurring in a fixed time interval of length t_M is computed from the Poisson distribution as follows (see any good reliability text):

$$P_i(t_M) = \frac{(\lambda t_M)^i e^{-\lambda t_M}}{i!}.$$

Since i = 1, then

$$P_{21} = P_1(t_M) = \lambda t_M e^{-\lambda t_M}.$$

It was assumed earlier that MTBF = 100 hours, therefore

$$\lambda = \frac{1}{\text{MTBF}} = \frac{1}{100} = 0.01 \text{ failures per hour.}$$

Suppose t_M = 8 hours. Then

$$P_{21} = 0.01(8)\, e^{-0.01(8)} = 0.0739.$$

P_{23} (Pr. of No System Failures)

The probability of no system failures is found by substituting i = 0 in the equation for $P_i(t_M)$ given previously:

$$P_{23} = \frac{(\lambda t_M)^0 e^{-\lambda t_M}}{0!} = e^{-\lambda t_M}.$$

This is the familiar equation for reliability (assuming a series system with exponential failures), which is simply the probability of zero failures during the mission of duration t_M.

Since $\lambda = 0.01$ failures per hour and $t_M = 8$ hours

$$P_{23} = e^{-0.01(8)} = 0.9231.$$

P_{32} (Pr. That Downtime is 0.5 Hours or Less)

If it is assumed for simplicity that the only source of downtime is system restoration following a failure, that failures are detected immediately, that repair tasks are uninterrupted, and that necessary resources (technicians, spares, etc.) are available immediately, then downtime is simply active repair time. In this case we shall assume that the Generalized Maintainability Method (GMM -- see Appendix B) was used to predict the probability distribution of repair time so that the distribution of repair time, $F(t_R)$, is given in graphical form as shown in Figure A-3. According to the curve for $F(t_R)$, a t_R of 0.5 hours or less has a probability of 0.67. Therefore

$$P_{32} = 0.67.$$

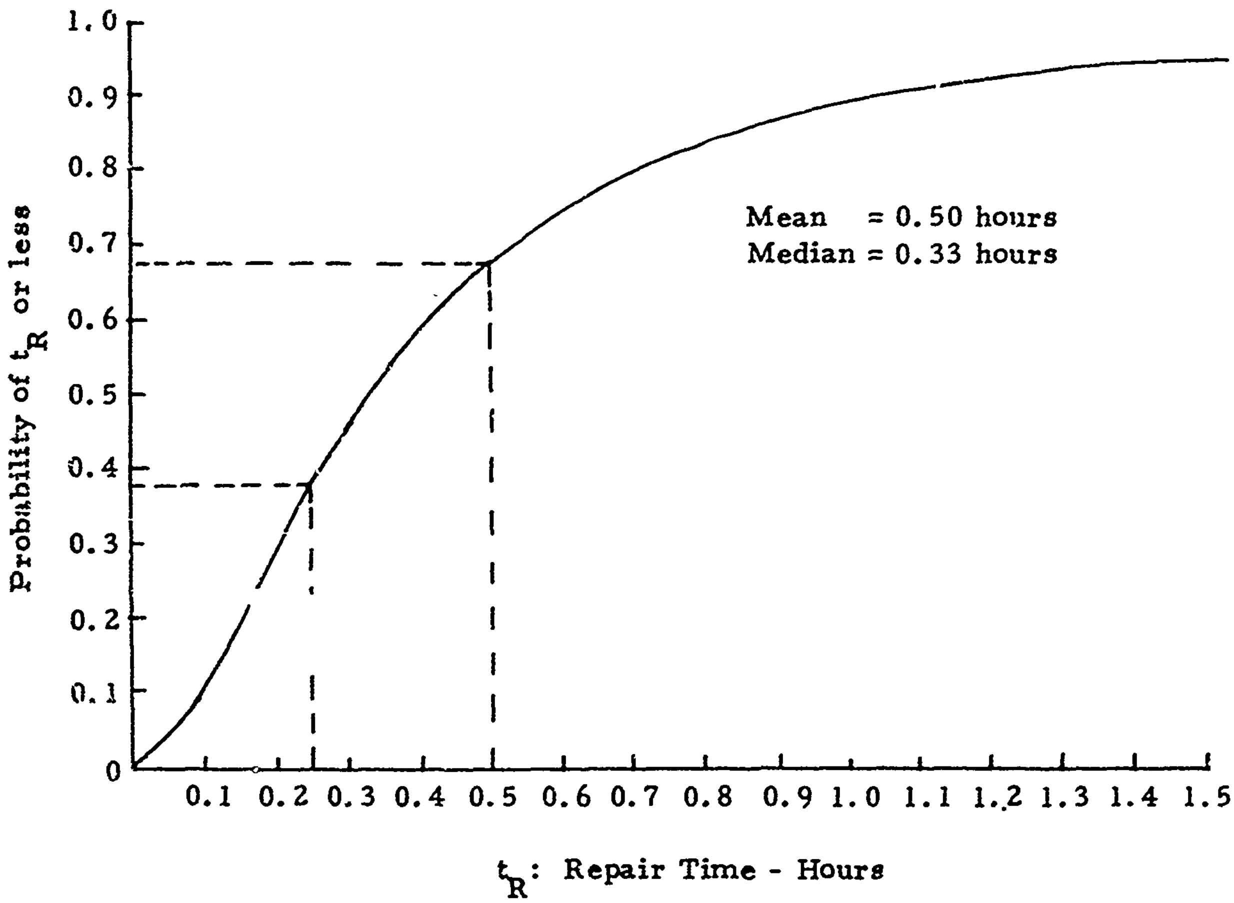

Figure A-3. Example repair time distribution, $F(t_R)$

P_{41} (Pr. that Initial Restore Time is 0.25 Hours or Less)

If the system is down when warning occurs, it could be at any point in the repair process. At worst the repair may have just begun, and consulting Figure A-3, we see that the probability of repair within 0.25 hours is 0.37. Obviously, if the repair is just being finished, the probability that $t_R \leq 0.25$ hours is 1.0. Suppose the repair is half complete -- what is the probability that $1/2\ t_R \leq 0.25$ hours? This is simply the probability that $t_R \leq 0.5$ hours, which is 0.67. It is apparent that the repair process is equally likely to be at any point from beginning to end (given that the system was down initially). Therefore, if we integrate over all remaining fractions of task to be completed from 1 to 0, the average probability is an estimate of P_{41}. An approximation can be achieved by computing maximum allowable repair time for equally-spaced increments of fraction-of-repair-remaining, taking the associated probabilities from Figure A-3, and finding their average. This computation is shown in the following table:

Fraction of Repair Remaining (f)	Max. Total Repair Time Consistent with Remaining Fraction Being Completed Within 0.25 hrs. ($t'_R = 0.25/f$)	Probability from Figure A-3 ($Pr(t_R \leq t'_R)$)
1.0	0.25	0.37
0.9	0.28	0.43
0.8	0.31	0.47
0.7	0.36	0.54
0.6	0.42	0.60
0.5	0.50	0.67
0.4	0.63	0.76
0.3	0.83	0.85
0.2	1.25	0.93
0.1	2.50	0.98
0	∞	1.00
	Ave. Pr.	0.69

Accordingly, the probability of repair within 0.25 hours given the system was down at warning and could be at any point in its repair cycle. is

$$P_{41} = 0.69.$$

P_{51} (Pr. that Task Accuracy is 0.90 or Greater)

Assuming that we have experimental or field data from which probability distributions of task accuracy can be estimated, the main modeling task is to determine how these combine across the two tasks to provide net accuracy of the system performance output. The way accuracies combine depends on the exact nature of the tasks, their interaction and other factors. For illustrative purposes, suppose the output of Task A is the input to Task B and that accuracies are multiplicative, e.g., if Task A is 90 percent accurate and Task B is 80 percent accurate, the output is $0.90 \times 0.80 = 0.72$ or 72 percent accurate. (Certain types of information processing provide examples of this type of task.) In that case, the overall task accuracy, θ, could very well be related to the individual task accuracies θ_A and θ_B according to the relation

$$\theta = \theta_A \theta_B$$

where θ's are expressed in decimal form. The problem is to determine the distribution $H(\theta)$ when the distributions $H(\theta_A)$ and $H(\theta_B)$ are given.

One common approach is to use Monte Carlo methods using high speed digital computers. A pair of values, θ_A and θ_B, are randomly sampled from the distributions $H(\theta_A)$ $H(\theta_B)$ and substituted in the above equation to find a value of θ. Many repetitions of this procedure enable the distribution $H(\theta)$ to be constructed.

An analytic approach can also be used which depends on the combinatorial properties of moments and cumulants, which are readily derived from the distributions. The method has been called the Method of Moments, and is described in the documentation for the Generalized Maintainability Method (see Appendix B).

Suppose accuracies for Task A and Task B are both distributed normally with the following parameters:

	Mean	Standard Deviation
Task A	0.96	0.01
Task B	0.95	0.01

It is assumed that the distributions represent stochastically independent random variables. The distributions for Tasks A and B are shown in Figure A-4. The distribution of output accuracy is obtained by combining the two distributions as indicated by the relation $\theta = \theta_A \theta_B$ given earlier, and is also shown in Figure A-4.

According to the distribution, the probability that output (combined) accuracy is 0.90 <u>or less</u> is 0.25. Since we want the probability that accuracy is 0.90 or greater, we take $1 - 0.25 = 0.75$. Therefore

$$P_{51} = 0.75.$$

This is one of many possible examples of how a performance measure is introduced into a system effectiveness model in relation to a mission criterion.

<u>P_{61} (P. that Total Task Time is t_M or Less)</u>

In addition to task accuracy, task time is another performance attribute of the system which provides an effectiveness criterion. Frequently, task time and task accuracy are interdependent in some way (especially in man-machine systems) and need to be considered jointly. To facilitate the example, however, we shall assume this is not the case and that task time can be analyzed independently.

The criterion given earlier states that the total task time must be t_M hours or less. Thus, for any given mission performance

$$t_A + t_B = t, \quad (P_r(t \leq t_M) = P_{61}.$$

Analysis of the ESM in Figure A-1 shows that after starting the mission, only one possible event path exists which is consistent with mission success: $E_3 \longrightarrow E_4$. In order to determine the overall probability that total task time is 0.5 hours or less, it is necessary to combine the individual task (event) - time distributions to obtain the overall

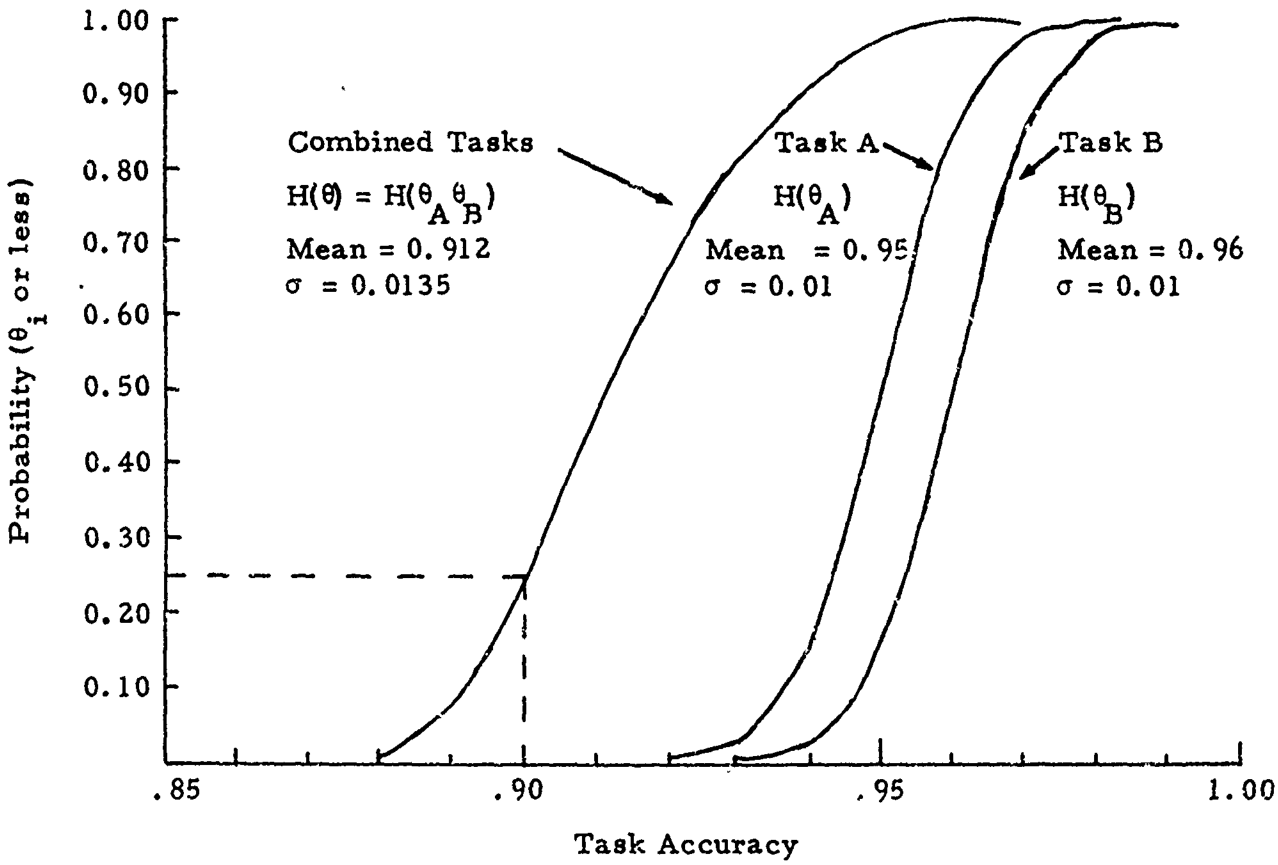

Figure A-4. Distribution of individual and combined task accuracies

distribution. Since the task times are additive, the equivalent operation on distributions is convolution, denoted by the asterisk (*). Thus

$$\text{if} \quad t = t_A + t_B \qquad (t,\ t_A \text{ and } t_B \text{ are random variables})$$

$$\text{then } G(t) = G(t_A) * G(t_B).$$

The convolution operation simply means that all possible combinations of values from the individual distributions, appropriately weighted by their probabilities, are combined into a new distribution. This is frequently carried out by simulation procedures using Monte Carlo methods. The Method of Moments technique is more convenient and less expensive, however, and was used to combine distributions in this example. The procedure is documented as part of the Generalized Maintainability Method.*

Assume that Tasks A and B have lognormal task-time distributions as shown in Figure A-5. Their convolution provides the distribution shown at the right of Figure A-5, which gives the probability that task time is any value _t_ or less. Since t_M = 8 hours and the corresponding probability is 0.96, then

$$P_{61} = 0.96.$$

Computation of System Effectiveness

The necessary probabilities have now been derived and are summarized as follows:

$$P_{11} = 0.9950$$

$$P_{12} = 0.0050$$

*Naval Electronics Laboratory Center, Generalized Maintainability Method (GMM), Technical Document 152, 23 November, 1971.

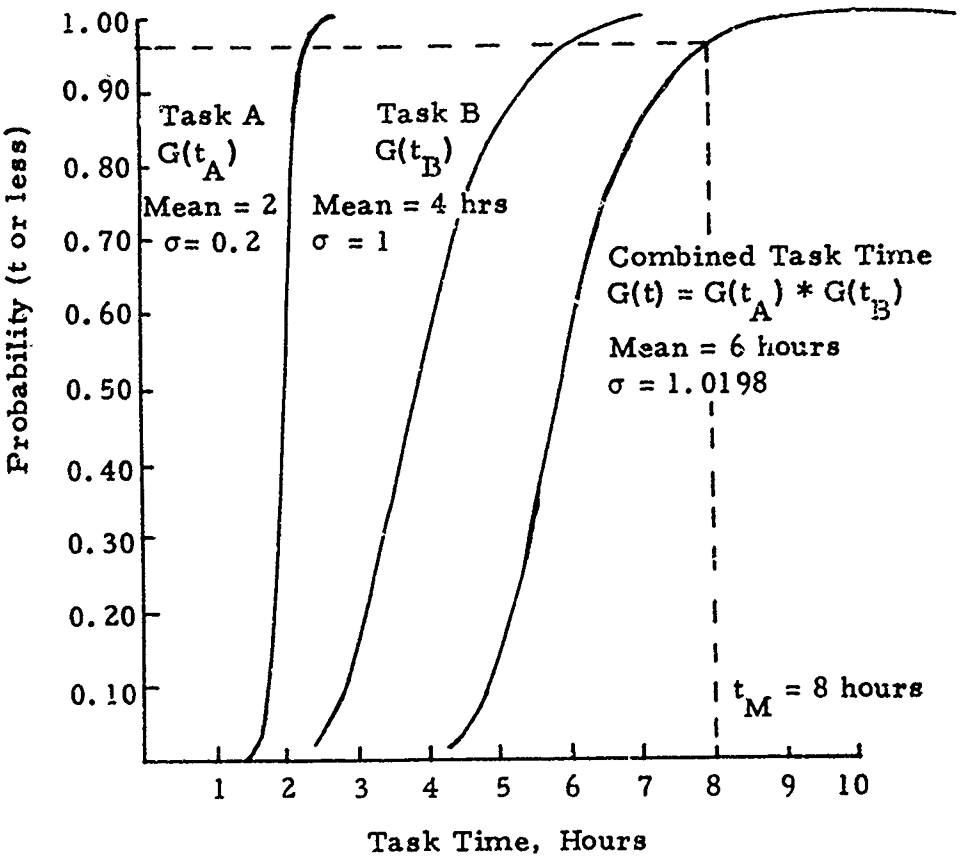

Figure A-5. Individual and combined task-time distributions

$$P_{21} = 0.0739$$

$$P_{23} = 0.9231$$

$$P_{32} = 0.67$$

$$P_{41} = 0.69$$

$$P_{51} = 0.75$$

$$P_{61} = 0.96$$

From Equation A-1, system effectiveness is expressed as

$$SE = (P_{12}P_{41} + P_{11})\,[P_{51}P_{61}(P_{21}P_{32} + P_{23})]$$

Substitution of the above values provides

$$SE = (0.0050 \times 0.69 + 0.9950)\,[0.75 \times 0.96\,(0.0739 \times 0.67 + 0.9231)]$$

$$= 0.9985\,[0.7003] = 0.6992.$$

An effectiveness of 0.6992 means that the system can be expected to achieve its mission objectives less than 70 percent of the time. In most cases, this would probably be considered unacceptable. Inspection of the terms of the model shows that the major problem is the low value of P_{51}(=0.75), which is the probability that task accuracy is 0.90 or better. If this is a man-machine system, we might discover that the human operator is the weak link and assign the problem to the Human Factors Department. Various approaches might be considered, such as automation to eliminate much or all of the operator's role, redesign of the task, redesign of equipment to make the task easier, use of more-highly-skilled operators, etc. Along with assignment of the problem, a goal should be allocated. Assuming all terms except P_{51} remain constant, and assuming the SE requirement were 0.90, then

$$0.90 = 0.9985\,[0.9337\,P_{51}]$$

and

$$P_{51} = 0.9654 \text{ (design goal).}$$

Thus, the Human Factors Department has the problem of increasing P_{51} from 0.75 to 0.97. If this cannot be completely achieved, then improvement in the other terms must also be considered. In any event, trade-offs involving costs, schedule and other factors should be carried out to decide on the set of design improvement approaches which provides greatest system value.

Referring back to Figure A-1 and Equation A-1 for SE, it car readily be seen that the probabilities can be grouped in accordance with the partitions Availability, Dependability and Capability as follows:

A = Pr.(System Available) = $P_{11} + P_{12}P_{41}$ = (System Available at Warning) + (System Unavailable at Warning) x (System Repaired Within Warning Time) = 0.9985

D = Pr.(System Dependable) = $P_{23} + P_{21}P_{32}$ = (No System Failure) + (One System Failure) x (System Restored Within Allowable Downtime) = 0.9726

C = Pr.(System Capable) = $P_{51}P_{61}$ = (Task Accuracy Sufficient) x (Task Time Within Allowable Time) = 0.7200

and

$$SE = (A)(D)(C) = (0.9985)(0.9726)(0.7200) = 0.6992.$$

This is the same result we obtained before. It is interesting to note that availability of the system in this case is not simply $A_i (= P_{11})$ which, alone, would have underestimated system availability; but also includes a term for availability within warning time due to repair of a down system. This illustrates the need for caution in using simple formulations such as the one for A_i without first constructing the overall effectiveness model.

It should also be pointed out that the simplicity of the illustration in itself could be misleading, since many practical cases do not provide independent probabilities for A, D and C which are multiplicative in the simple fashion provided by the foregoing example. Generally, matrix calculations or their equivalent are required (see the WSEIAC documentation, for example). In those cases, the general approach used in the example still holds, except that more-detailed diagrams and models are required to account for the dependencies among variables. For this reason, partitioning of the model into A, D and C terms is not generally recommended at the overall level, and the entire diagram must frequently be carried along to lower levels of indenture. Unfortunately, adequate discussion of the required techniques is beyond the scope of this manual. To avoid pitfalls, the manager should make sure that competent analysts are used who are skilled in the application of probability and statistics to practical system modeling.

APPENDIX B

THREE EFFECTIVENESS-RELATED PROCEDURALIZED METHODS

B.1 Generalized Maintainability Method (GMM)

The Generalized Maintainability Method (GMM) is a generalized procedure for the analysis of system maintainability and the estimation or prediction of time-oriented measures of maintainability. Outputs are in a form required for effec iveness modeling of the type discussed in Appendix A. In order to achieve generality and encompass a maximum range of application the procedure is for the design of a useful maintainability model rather than for the routine application of a predesigned model. The procedure is applicable to all types of systems, to all acquisition phases, to all levels of analysis, and to all situations. It may be used on electronic, electromechanical, mechanical, and hydraulic systems, from the equipment level to system level, and for shipboard, airborne, or other operational environments. The basic parameters of measurement are any time-oriented maintainability parameters, corrective or preventive, ranging in complexity from active repair time and associated man-hours to operational downtime. Since distributions are produced if desired, any parameter or percentile of the distribution may be an output.

The GMM modeling technique incorporates an ESN diagram (similar to Figure A-1) which displays the alternative sequences of events which can potentially take place in transitioning from initial system states in which maintenance requirements are implied, to subsequent system states in which maintenance has been performed. The ESN can be used to represent any level of system, subsystem, or equipment complexity. Structuring the various system assumptions selected for analysis will result first in the design of an initial or overall ESN (or series of such ESN's) which represents the maintenance/support concept for the system. Continued application at lower levels of indenture will result in detailed ESN's which represent specific maintenance actions.

The alternative assumptions about the states of the system and the possible sequences of events which can change the system from one state to another produce a network containing junctures from which alternative branches are defined. The basis for estimating probabilities for each of these branches will depend upon the type of branch being considered. Where branches depend upon the existence of particular

failures, probabilities are obtained from reliability data. Branches may depend upon alternative diagnostic strategies, alternative test facilities, support provisions, and mission or environmental frequency-of-occurrence data.

The basis for estimating the range of possible durations for the maintenance actions or events will depend upon the level of analysis and the availability of retrievable, historical data. Although objective data are preferable, it is recognized that the best available data will sometimes be in the form of estimates made by expert, knowledgeable individuals who are familiar with the system in question, and/or with the component maintenance events which are similar in other, existing systems. GMM accepts data from any source and in any combination.

The initial ESN displays both the time-consuming maintenance actions or events, and the intermediate states of the system and mission which aid the analyst in formulating maintainability measures. In calculating the overall time distribution for these measures, the initial ESN is converted into a tree diagram (similar to Figure A-2) which displays the event sequences in a form which is convenient for tracing alternative paths. The tree diagram displays a finite random process which is defined by the following characteristics:

- From a fixed starting point (state), any one of a finite number of events can occur.
- For each possible event, a finite number of subsequent events can occur.
- The process eventually ends in one of a finite number of well-defined terminal states.

A path through a tree diagram or ESN is a single-thread sequence of events leading from an initial state to a terminal state.

Time distributions may be computed either by simulation or analytic procedures. The strategy for calculation of the combined time distribution by analytic procedures is described in the GMM documentation.

Further information about GMM may be obtained from the Naval Electronics Laboratory Center, Code 4100, San Diego, California. Technical Document 152 (November 1971) describing and illustrating the procedure may be obtained from the above source by qualified users.

B.2 Generalized Effectiveness Methodology (GEM)

GEM provides a highly flexible computerized capability for analyses of the Availability and Dependability terms of a system effectiveness model. It was developed to permit ease and rapidity of probabilistic analysis of complex systems characterized by on-line repair capability with limited resources, long mission times, and extensive redundancy. These characteristics generally lead to a more-complex system model when one recognizes the possibility that redundant portions of a system may be repaired while a mission is in process. Ignoring this possibility generally results in an unduly pessimistic estimate of system mission reliability. However, the computations required by this more-complex system model are prohibitive for systems of any degree of complexity unless machine methods are employed. GEM was developed so that the system models incorporating these important factors can be computerized and exercised with minimal effort on the part of the user. GEM is an analytical tool which provides the systems Reliability/Maintainability/Availability/Effectiveness analyst with the means to analytically model a complex system against equally complex multiphase mission scenarios and to perform sensitivity analyses quickly and economically under dynamically changing mission revisions, system design configurations, changes in failure definitions, and trade-off studies.

The following summary of GEM capabilities is taken from the Handbook of Systems Effectiveness Models, and is an example of the type of information provided:

TITLE:	Generalized Effectiveness Methodology (GEM)
LANGUAGE:	GEM Language
COMPUTER:	CDC 6600
DATE OPERATIONAL:	August 1966
DESCRIPTION:	The Generalized Effectiveness Methodology (GEM) is a user-oriented computer program for computing one or more of a set of system statistics such as reliability, availability, mean up time, mean down time, effective failure and repair rates, restore time distributions and

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<u>LANGUAGE:</u>	GEM Language
<u>COMPUTER:</u>	CDC 6600
<u>DATE OPERATIONAL:</u>	August 1966
<u>DESCRIPTION:</u>	The Generalized Effectiveness Methodology (GEM) is a user-oriented computer program for computing one or more of a set of system statistics such as reliability, availability, mean up time, mean down time, effective failure and repair rates, restore time distributions and

repairmen utilization. The inputs required are the system model and data in the form of parameters of distributions of times to failure and times to repair for the elementary components of the system. The system model essentially includes the reliability configuration of the system, a set of system failure definitions, and logistic information in terms of repair crews, spares pools and priorities. The system model may include any reliability structure. For systems without repair, the elementary components can be characterized by any one of five distributions of times to failure: exponential, Weibull, gamma, log normal, and truncated normal distributions. For systems with repair, distributions of times to failure, repair, or replacement for the elementary components are assumed to be exponential only. A user-oriented high level source language is used. Inputs written in the GEM Language are used by the GEM Compiler to generate a FORTRAN program. Depending on the problem, solutions by GEM are obtained either by combinatorial methods or by solving a set of linear differential equations describing the system state probabilities, or both. Answers are given in the forms of tables and plots.

COMMENTS: The original GEM program was updated aperiodically. Documents published in 1971 include the Capability Summary (TD 131), User's Manual (TD 114), Reference Manual (TD 115), and Mathematics Libary Manual (TD 116).

SOURCE: For documents or further information, contact Naval Electronics Laboratory Center (Code 4100), San Diego, California; or Naval Ships Engineering Center (Code 6102C), Hyattsville, Maryland.

B.3 Design Disclosure for Systems and Equipment (DDSE)

Throughout the system life cycle there are continuing requirements for various types of effectiveness analysis. These analytic functions are generally performed by contractor staff organizations, in-house Navy groups, or independently contracted research firms. The analyst expends considerable time in research and data collection before he can conduct his effectiveness study. Typically he is forced to devote more than half of his time to learning the system, collecting technical data, and defining the system in a manner required for analysis. With DDSE the preparation elements of an analyst's job are essentially completed for him, and the corresponding costs can be averted. Similarly, the functions of system engineering, integrated logistics support and design engineering are greatly benefited by the increased effectiveness and efficiency of engineering/management communication provided by DDSE. Design review is facilitated through consistency, standardization, completeness and ease of interpretation of documentation, and evaluation of the findings of effectiveness analysis is more-readily carried out by managers and engineers alike. In addition, preparation of technical manuals* and optimal location of test points** are facilitated.

*See MIL-M-24100A. Manuals, Orders and Other Technical Instructions for Equipment and Systems dated 15 June 1966, which calls for symbolic integrated maintenance manuals (SIMM) in essentially the same format.

**See MIL-STD-1326, Test Point Selection and Interface Requirements for Equipment Monitored by Shipboard On-Line Automatic Test Equipment dated 16 January 1968, which requires application of the design disclosure approach to test point selection.

MIL-HDBK-226 provides the basic disclosure for DDSE. A useful introduction is the "Manager's Implementation Guide to MIL-HDBK-226 [June 1968], Design Disclosure for Systems Equipment."*

Four basic structures comprise the DDSE set. They form the fundamental vehicle for transmitting design information between Navy and contractor activities jointly working together for one objective, the deployment and utilization of an effective system. The structures are:

- Blocked Schematics
- Detailed Block Diagrams
- Blocked Texts
- Design Outlines

Varieties of these format types are used to map design configurations in an understandable manner during the entire acquisition cycle, from concept through completion of production models. They consolidate in a unified scheme basic data required in a variety of engineering disciplines, thus becoming a single source document containing all the required design, planning and effectiveness information.

Examples of the four basic DDSE elements (from NELC TD154) are shown in Figures B-1 through B-5. Figure B-1 is an example of a blocked schematic for a voice amplifier. "System," assembly (PC board), and circuit boundaries are shown as shaded areas of varying intensity. To simplify functional analysis, the blocked schematic is translated into a detailed block diagram (Figure B-2) which shows only the functions. Accompanying the blocked schematics and detailed block diagrams are blocked texts (Figures B-3 and B-4) which provide a written explanation of the circuit functions and operation of the functions and assemblies. Figure B-5 illustrates the design outline which accompanies the other DDSE elements. The design outline is a shorthand form for describing system operation, requirements, and dependencies. Its primary purpose is to illustrate the functional dependencies

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*Naval Electronics Laboratory Center, Manager's Implementation Guide to MIL-HDBK-226 [June 1968], Design Disclosure for Systems and Equipment, Technical Document 154, 14 December 1971. (Qualified users may obtain copies from Code 4100, NELC, San Diego, California)

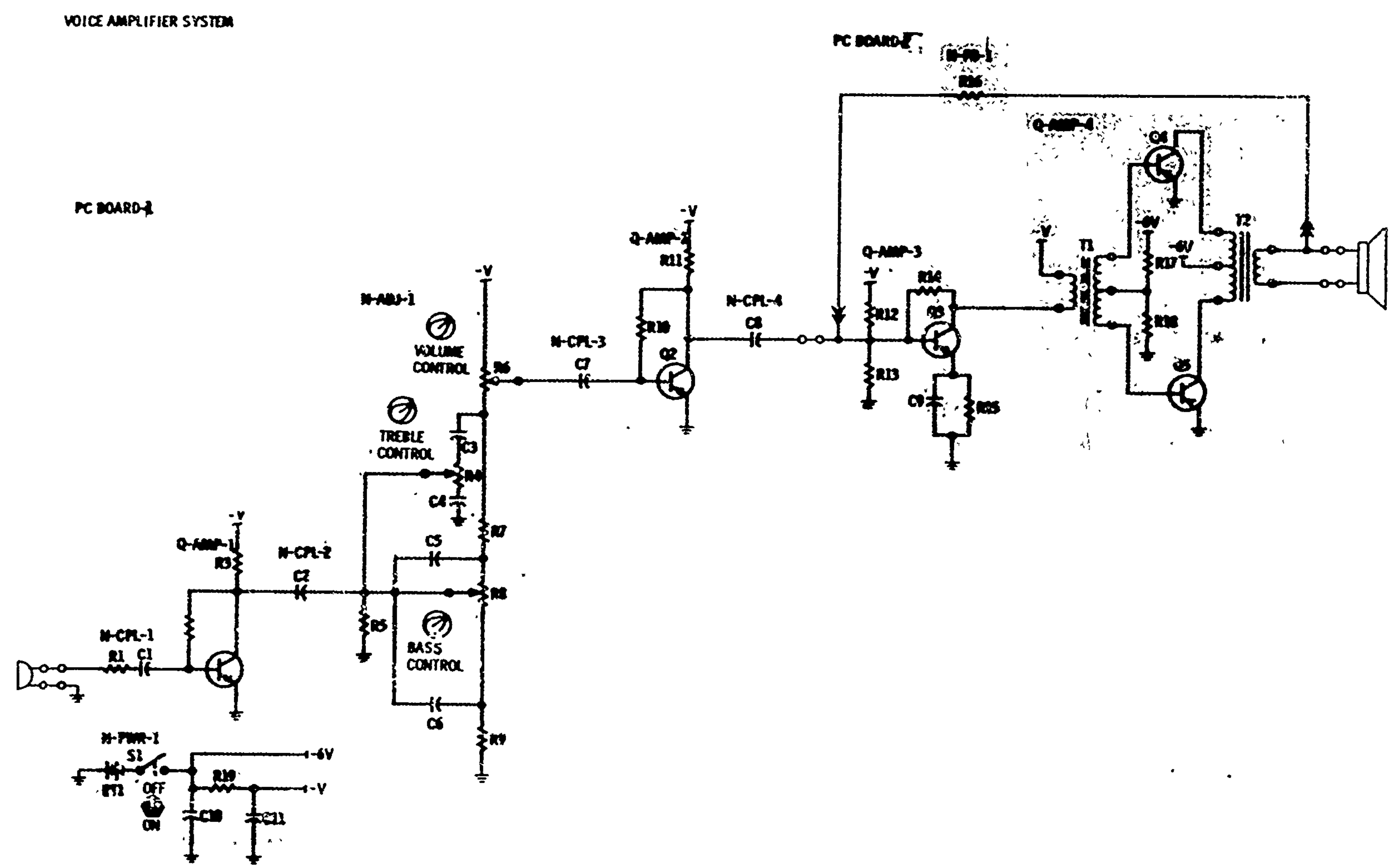


Figure B-1. Blocked schematic of Voice Amplifier showing system, assembly and circuit boundaries

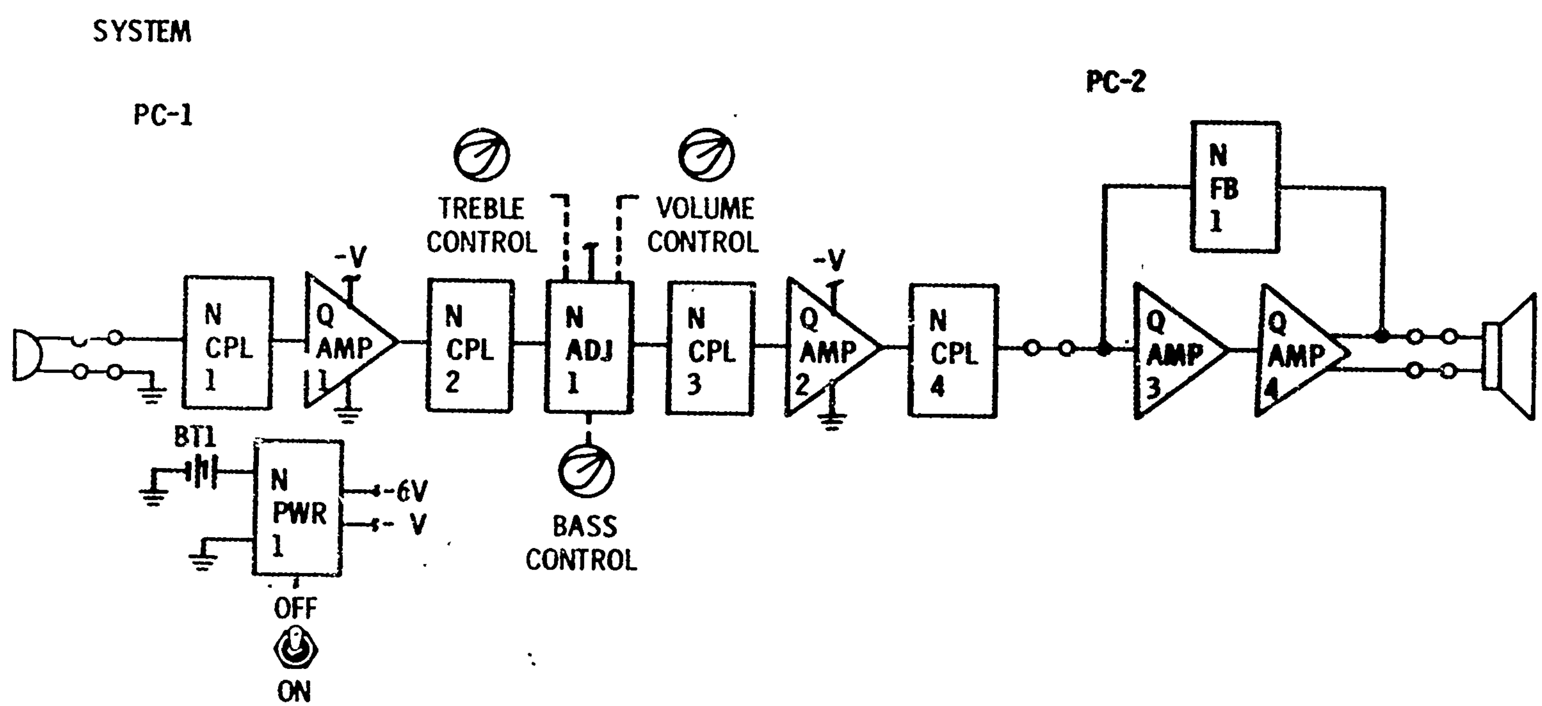


Figure B-2. Detailed block diagram of Voice Amplifier

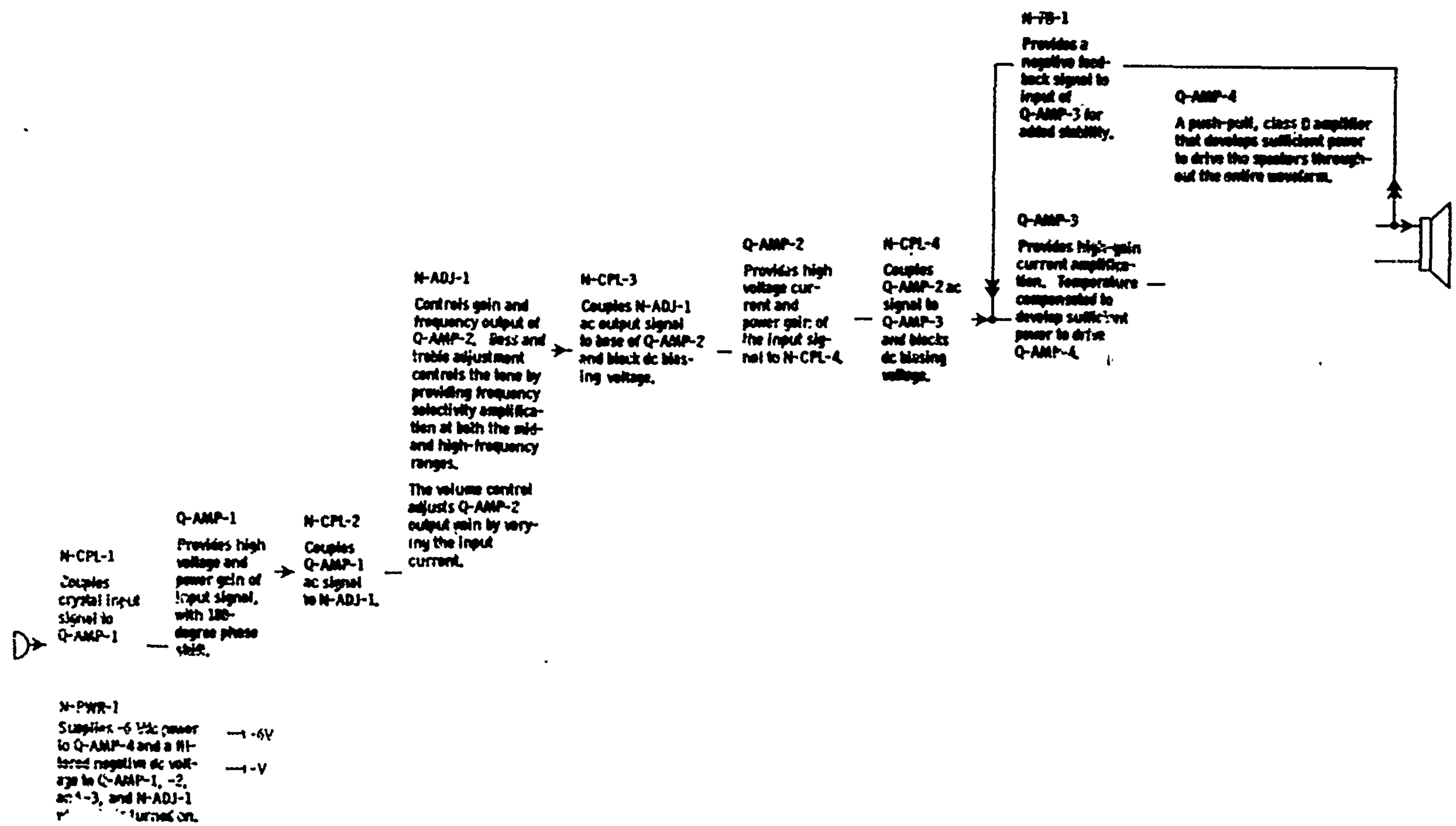


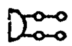
Figure B-3. Blocked text to accompany blocked schematic.

ASSEMBLY

Six-volt four-stage voice amplifier which provides 300 milliwatt output signal with a 10% distortion factor.

PC BOARD-1

Provides two-stage amplification of input signal. Output of Q-AMP-1 is controlled by a 50K linear taper bass adjustment, a 50K linear taper treble adjustment, and a 10K audio taper volume control adjustment. Q-AMP-2 further amplifies the controlled signal and sends it to PC BOARD-2. N-CPL-1 through -4 couples the signal through each stage of amplification or tuning. N-PWR-1 furnishes minus 6 Vdc to PC BOARD-2 and a filtered negative voltage to PC BOARD-1 and -2 for the various amplification stages. On-off control is by means of the toggle switch in N-PWR-1.



PC BOARD-2

Provides power amplification of signals received from PC-BOARD-1. Q-AMP-3 develops the driving power for Q-AMP-4. Q-AMP-4, a push-pull power amplifier, develops sufficient power to drive the speaker. N-FB-1 is a degenerative feedback returned to the input of Q-AMP-3.

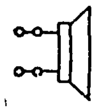


Figure B-4. Blocked text to accompany detailed block diagram.

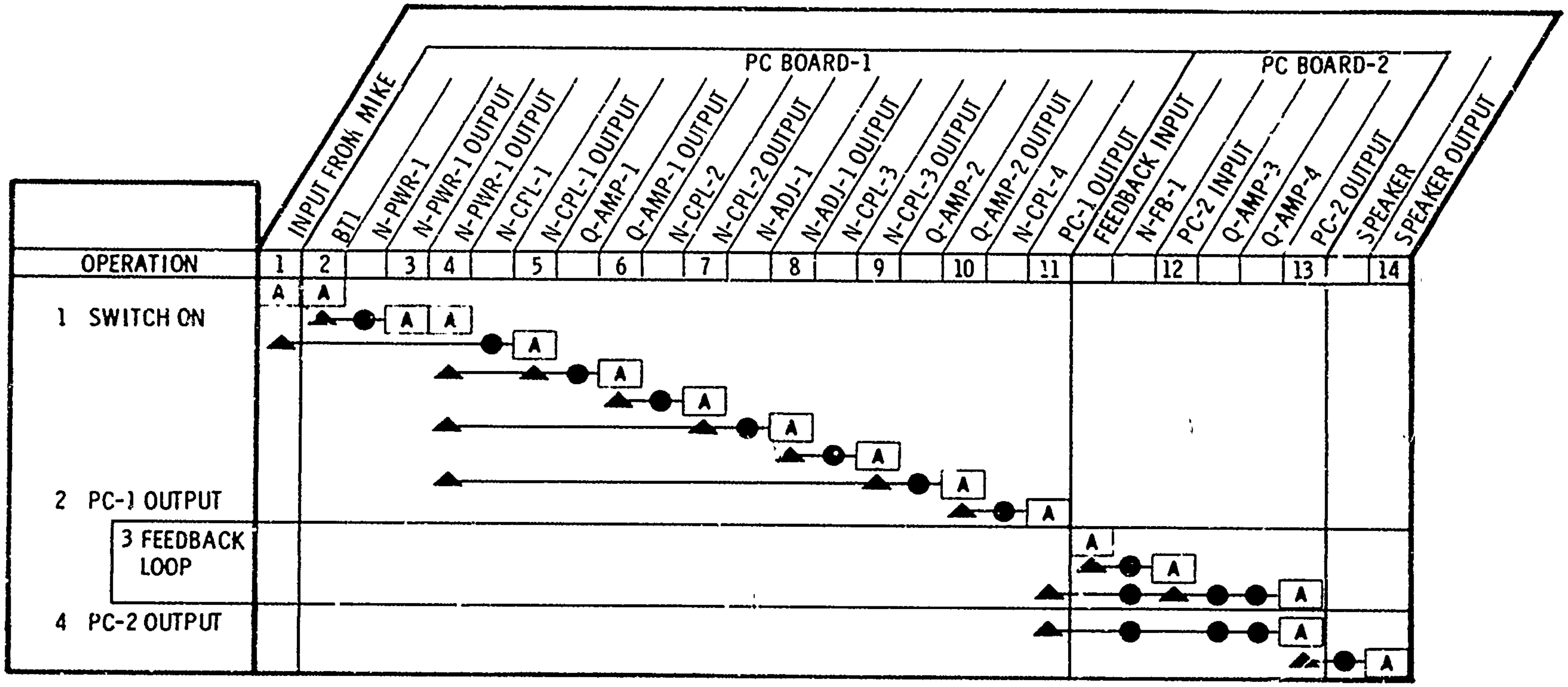


Figure B-5. Design Outline for Voice Amplifier Circuit

Explanation:

1 Switch On. With battery (BT1) voltage available (▲), and with the power supply (N-PWR-1) operating properly (●), two separate output voltages will be available ($\boxed{A}$) at the power supply output.

2 PC1 Output. With a voltage available (▲) at the output of amplifier Q-AMP-2 and with coupling network N-CPL-4 operating properly (●), a signal will be available ($\boxed{A}$) at the output of PC-1.

3 Feedback. With a voltage available (▲) at the N-FB-1 input, and with the feedback network N-FB-1 operating properly (●), the feedback signal will be available ($\boxed{A}$) at the input to PC-2.

4 PC-2 Output. With a voltage available (▲) at the output of Q-AMP-3, and also with voltage available (▲) at the power supply output N-PWR-1 and amplifier Q-AMP-4 operating properly (●), a signal will be available ($\boxed{A}$) at the output of PC-2.

of a system, black box, assembly, subassembly or circuit. It is a logic map of the system operation, interdependencies, input requirements, output requirements, and operating sequences. Its primary value is system analysis rather than system design; it describes event dependencies and requirements as opposed to how the event is made to occur. The design outline provides an important input to aid in structuring the effectiveness model.

In addition to the basic DDSE set, various types of supplemental data keyed to the basic set are also provided. One supplemental sheet described in MIL-HDBK-226 is the system-equipment description, which presents command-level information to both the procuring and producing activities, and serves as a working paper for the contracting office. Since the system-equipment description is of standard format, direct overall comparison of competing designs is aided.

Other supplemental data sheets which may be required include:

- System effectiveness/system value studies
- Reliability/maintainability analyses
- Tradeoff studies
- Quality assurance reports (MIL-Q-9858)
- Manufacturing drawings
- Interface control drawings, such as cabling and piping
- Maintenance procedures
- Alignment/checkout procedures
- Computer software documentation
- Human factors data, including operational sequence diagrams (MIL-H-46885)
- Integrated Logistics Support (ILS) data

- Packaging data, such as equipment layouts, module location diagrams

- Cost data

- Data sources, etc., as required separately by DD-1423

DDSE is prepared with the users in mind, the users comprising many engineering and management disciplines, each with varied backgrounds, talents, and project responsibilities. All pertinent system criteria and design information are addressed on the applicable DDSE forms. The design disclosure information contained on the DDSE forms will be the basis for many decisions having major impact on the success or failure of the system.

MIL-HDBK-226 defines design disclosure formats capable of providing any level of system detail while allowing the user a great degree of flexibility in their preparation. The complete set of formats described in that handbook include the following:

- Master Block Diagram and Text

- Master Design Outline

- Intermediate Block Diagram and Text

- Intermediate Design Outline

- Detailed Block Diagram and Text

- Power Distribution Diagram and Text

- Detailed Design Outline

- Blocked Schematic and Text

- Front Matter

- Supplemental Information.